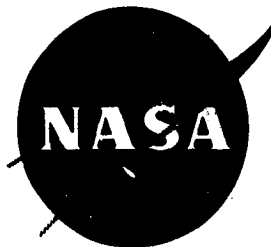


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WESTINGHOUSE REPORT NO. WAED 63.11E



N64-25918

Code-1
Nasa Or-55800
Cat. 06

SPACE ELECTRIC POWER SYSTEMS STUDY
D.C. TO D.C. CONVERTERS FOR NUCLEAR-THERMIONIC ENERGY SOURCES

VOLUME 5

CONTRACT NO. NAS 5-1234,
AMENDMENT 6

Final Report For The Period
May 3, 1963 To December 3, 1963

PREPARED FOR THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



245 4213

Westinghouse Electric Corporation
AEROSPACE ELECTRICAL DIVISION
LIMA, OHIO

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t SPACE ELECTRIC POWER SYSTEMS STUDY;

D-C TO D-C CONVERTERS FOR NUCLEAR THERMIONIC ENERGY SOURCES, VOLUME 5

VOLUME 5

2# Final Report, 3 May 1963 - 3 Dec. 1963

cite only
NASA Contract NAS 5-1234, Amend. 6

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PREFACE

This report is the result of work performed by the Aerospace Electrical Division of Westinghouse Electric Corporation for the National Aeronautics and Space Administration under Contract NAS5-1234, Amendment 6. The work was under the direction of E. A. Koutnik, Technical Director, Nuclear Power Technology Branch, Lewis Research Center, Cleveland, Ohio.

ABSTRACT

Volume 1

This volume describes the general system arrangement and defines those system components necessary to efficiently (weight and power losses) supply a variable voltage d-c load at constant power. The system arrangement from turbine shaft to d-c bus includes: a generator; an exciter-regulator, for generator excitation control; a transformer; a rectifier; and switchgear. The switchgear includes circuit breakers, tap changers, and bank switches as needed.

The components and materials for each system component were selected on the basis of temperature, frequency, power rating, and availability. In most cases, the generator magnetic materials are Hiperco 27 for stator and SAE 4340 for rotor. The conductors are copper insulated with an inorganic material. Transformer materials include silicon-iron for core; copper conductors; and insulation of mica, glass and asbestos. Silicon semiconductor devices were chosen in all cases because of weight and power ratings.

The general approach to cooling each system component is discussed along with the mathematical development of the approach chosen. All components are cooled with a liquid coolant. The coolants used were potassium for the generator, NaK or potassium for high temperature power conditioning equipment, and MIPB for low temperature power conditioning equipment.

A method of determining size, weight and impedance of transmission lines is developed. The approach was to develop equations for the resistance of hollow and solid conductors, then balance the conductor power losses (I^2R) to the amount of power that can be radiated from the surface of the conductor.

Volume 2

This volume provides all the parametric data developed for each system component of the one-to-ten megawatt study. Generator ratings of one, two, five, and ten megawatts at speeds from 10 to 24 thousand rpm and coolant temperatures between 500F and 1100F are considered. All generator designs are limited by the allowable stress of the rotor material for a combination of speed and temperature. The combination usually decreases as the rating increases. Because of these limitations, the specific weight generally increases with rating. Additional designs at lower speeds, below 10,000 rpm, were added to the study because NASA indicated that turbine speeds might have to be decreased. Designs at one, two, and five megawatts are included.

The effect of advanced materials on generator weight and losses are also examined. The effect of better magnetic and insulation materials caused weight reductions of about 25 percent and efficiency improvements of about 0.5 percent.

The one-, five- and ten-megawatt transformer designs with maximum temperatures of 500F, 1000F, and 1500F show that except for some limitations the electro-magnetic weight is practically independent of rating for equal operating conditions and efficiency. The designs also show that aluminum conductors offer no weight or efficiency advantage over copper conductors.

The parametric data for the exciter-regulator and the rectifier show that the silicon semiconductors are the best choice from a weight standpoint. The data also show that high-temperature devices do not offer any weight or efficiency advantage because their ratings are too low for this application.

Parametric data for circuit breakers, tap changers, and bank switches are included to evaluate the effect of step changes in direct voltage.

Volume 3

This volume provides three conceptual system designs based upon three missions. All designs are for one-megawatt ratings. The first design is based on a variable output voltage of 600 to 6000 volts. The second design is for a 4000-volt system and third is for a 20,000-volt system. The specific weights of the first and third system are about equal while system number 2 has the lowest specific weight. The second system is lighter because no transformer is required. See Section VII for a tabular summary of each of the systems.

Volume 4

This volume provides all the parametric data and one preliminary system design for the extended portion of this contract. The ratings of the parametric data are 250 and 500 kw at 5000 volts.

As shown by the preliminary design summary, the specific weight of this system is higher than the specific weight of the one-megawatt system. The primary reason for the increase is this system supplies auxiliary a-c loads. The generator operates at a lower frequency, and the general concept of weight savings as system ratings increase is borne out for this type of system in ratings below about one megawatt.

Volume 5

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This volume, reported under Contract NAS5-1234, Amendment 6, presents the results of an investigation of megawatt d-c to d-c converters to be used with space ion thruster electric propulsion systems when operating from a nuclear-thermionic energy source. The basic objective was to provide the following information:

1. Parametric data for d-c to d-c converters in the 0.5 to 5 megawatt power range.

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2. Elucidation of the problems that exist in the development of high power d-c to d-c converters,
3. Recommendations for further study and consideration for development of high power d-c to d-c converters.

Guidelines were established to give direction to the program effort. A preliminary design was made to identify the functional blocks that are common to all the converters considered. Based on the preliminary design, a parametric investigation was made for each functional block at several different power levels and input voltages.

The results of the parametric investigations are presented in a report for each functional block. The results include parametric data in tabulated and graphic form, identification of problem areas, analysis and recommendations. A weight, volume, and efficiency summary is given in Section V, page 196.

An analysis of the voltage transients caused by arcing faults in electric engines is presented in the appendix.

The scope of the study did not include the parametric investigation of complete converter systems. Only the basic functional blocks that make up a d-c to d-c converter were under consideration. Parametric data for the nuclear source, radiators, shielding and interconnecting conductors were not part of the study program.

AUTHOR

TABLE OF CONTENTS

Section	Title	Page
I	Introduction	1
II	Preliminary Design	2
A	Guidelines	3
B	Functional Block Description	5
III	Functional Block Analysis	21
A	Input Filter	22
B	Inverter Switching Circuit	35
C	Power Transformer	72
D	Power Rectifier	94
E	Output Filter	119
F	Switchgear	141
G	Drive Amplifier	144
H	Frequency Reference Oscillator	164
J	Voltage Regulator	175
K	Current Protection Circuit	187
IV	Reliability	194
V	Summary	196
VI	Conclusions and Recommendations	200
VII	Bibliography	202
VIII	Appendix	203
	Electric Engine Arc Suppression	

LIST OF FIGURES

Figure	Title	Page
1	1 MW(e) Nuclear Thermionic Space Powerplant Reactor Electrical Characteristics	4
2	D-C to D-C Converter Block Diagram	6
3	Inverter Circuit Schematic Diagrams	8
4	Radiator Specific Weight-vs-Average Coolant Temperatures	12
5	Input Filter Heat Load-vs-Power Output at 1000 Cycles per Second	25
6	Input Filter Weight-vs-Power Output	29
7	Input Filter Volume-vs-Power Output	30
8	Flow Rate-Temperature Rise Chart for Eutectic NaK	31
9	Input Filter Coolant Inlet Temperature-vs-Coolant Flow Rate for a One Megawatt, 1000 cps Inverter Frequency	32
10	Input Filter Coolant Inlet Temperature-vs-Inverter Switching Frequency	33
11	Inverter Module Circuits	37
12	Inverter Switching Element Power Losses	46
13	Inverter Heat Loads-vs-Power Output at 1000 Cycles Per Second	48
14	Inverter Heat Loads-vs-Switching Frequency for One Megawatt	49
15	Inverter Efficiency-vs-Switching Frequency for One Megawatt	50
16	Silicon Semiconductor Inverter Weight-vs-Power Output at 1000 Cycles per Second	59
17	Silicon Semiconductor Inverter Volume-vs-Power Output at 1000 Cycles per Second	60
18	SCR Inverter Coolant Inlet Temperature-vs-Coolant Flow Rate for One Megawatt, 1000 Cycle per Second Inverter Frequency	61

LIST OF FIGURES
(continued)

Figure	Title	Page
19	SCR Inverter Weight and Volume-vs-Inverter Switching Frequency for One Megawatt	62
20	SCR Inverter Coolant Inlet Temperature-vs-Inverter Switching Frequency for One Megawatt	63
21	Inverter High Temperature Design with Low Temperature Inductors - Coolant Inlet Temperature-vs-Coolant Flow Rate for Vapor Tube Thyratrons.	64
22	Inverter High Temperature Design with Low Temperature Inductors - Coolant Inlet Temperature-vs-Coolant Flow Rate for Inductors and other Low Temperature Components	65
23	Inverter High Temperature Design with High Temperature Inductors - Coolant Inlet Temperature-vs-Coolant Flow Rate for Thyratrons and Inductors	66
24	Inverter High Temperature Design with High Temperature Inductors - Coolant Inlet Temperature-vs-Coolant Flow Rate for Low Temperature Components	67
25	Inverter High Temperature Design Weight-vs-Switching Frequency	68
26	Inverter High Temperature Design with High Temperature Inductors Coolant Inlet Temperature-vs-Inverter Switching Frequency for High Temperature Coolant Circuit	69
27	Common Secondary Transformer Diagram	73
28	Transformer Relative Weight and Losses-vs-Inverter Switching Frequency	80
29	Transformer Specific Weight and Losses per KVA-vs-KVA Rating	81
30	Transformer Heat Loads-vs-Power Output at 400 Cycles per Second	82
31	Transformer Efficiency-vs-Input Voltage at 400 Cycles per Second	83

LIST OF FIGURES
(continued)

Figure	Title	Page
32	Transformer Weight-vs-Power Output at 400 Cycles per Second	88
33	Transformer Volume-vs-Power Output at 400 Cycles per Second	89
34	Transformer Coolant Inlet Temperature-vs-Coolant Flow Rate for One Megawatt, 400 Cycles per Second	90
35	Transformer Weight and Volume-vs-Inverter Switching Frequency for One Megawatt	91
36	Transformer Coolant Inlet Temperature-vs-Inverter Switching Frequency for One Megawatt	92
37	Schematic Diagram of Single Phase Bridge Rectifier Assembly	95
38	Silicon Diode Rectifier Assembly Power Losses-vs-Inverter Frequency for One Megawatt	104
39	Gas Tube Diode Rectifier Assembly Power Losses-vs-Inverter Switching Frequency	105
40	Silicon Diode Rectifier Assemblies Weight-vs-Power Output	112
41	Silicon Diode Rectifier Assemblies Volume-vs-Power Output	113
42	Silicon Diode Rectifier Assembly Coolant Inlet Temperature-vs-Coolant Flow Rate	114
43	Gas Tube Diode Rectifier Assembly Coolant Inlet Temperatures-vs-Coolant Flow Rate	116
44	Converter Output Ripple-vs-Inverter Switching Frequency	125
45	Output Filter Losses-vs-Inverter Switching Frequency for One Megawatt Converters	126
46	Output Filter Power Losses-vs-Power Output at 1000 Cycles per Second	127

LIST OF FIGURES
(continued)

Figure	Title	Page
47	Output Filter Weight-vs-Power Output for Transistor Converters	133
48	Output Filter Weight-vs-Power Output for SCR Converters	134
49	Output Filter Volume-vs-Power Output for Transistor Converters	135
50	Output Filter Volume-vs-Power Output for SCR Converters	136
51	Output Filter Weight-vs-Inverter Switching Frequency for One Megawatt	137
52	Output Filter Capacitor Coolant Inlet Temperature-vs-Coolant Flow Rate for One Megawatt	138
53	Output Filter Inductor Coolant Inlet Temperature-vs-Coolant Flow Rate	139
54	Switchgear Schematic Diagram	142
55	Drive Amplifier Functional Diagram for One Megawatt 20 Volt Input	146
56	Turn-Off Type Amplifier Module	147
57	Drive Amplifier Schematic Diagram for 2 Megawatt - 100 Volt Input	150
58	Drive Amplifier Schematic Diagram - SCR System	152
59	Drive Amplifier Heat Load-vs-Output Power	154
60	Drive Amplifier Weight-vs-Power Output	159
61	Drive Amplifier Volume-vs-Power Output	160
62	Drive Amplifier Weight-vs-Inverter Switching Frequency	161
63	Drive Amplifier Coolant Inlet Temperature-vs-Coolant Flow Rate for One Megawatt 300 and 600 Volt Input	162

LIST OF FIGURES
(continued)

Figure	Title	Page
64	Frequency Reference Oscillator Schematic Diagram	165
65	Frequency Reference Oscillator Heat Loads-vs-Output Power	168
66	Coolant Inlet Temperature-vs-Coolant Flow Rate For Frequency Reference Oscillator, Voltage Regulator, Current Protection Package	172
67	Voltage Regulator Functional Diagram	176
68	Voltage Regulator Error Detector Schematic Diagram	177
69	Bistable Magnetic Amplifier Schematic Diagram	178
70	Trigger Module Schematic Diagram	179
71	Zener Diode Clamp Schematic Diagram	180
72	Current Protection Schematic Diagram	188

LIST OF TABLES

Table	Title	Page
1	Inverter Circuit Comparison	9, 10, 11
2	Cooling System Comparison	17, 18
3	Input Filter Electrical Parameters	24
4	Input Filter Weights and Volume	28
5	List of Inverter Designs	36
6	Characteristics of Silicon Power Transistors	38
7	Characteristics of Silicon Controlled Rectifiers	39
8	Characteristics of Commutating Capacitors	40
9	Characteristics of Vapor Tube Thyratrons	41
10	Summary of Inverter Heat Loads	45
11	Summary of Inverter Efficiencies	47
12	Inverter Mechanical Design Parameters	57
13	Heat Loads for High Temperature Inverters	58
14	Power Transformer Weights and Losses	75
15	Power Transformer Electrical Parametric Data for 500 Kilowatt Systems	76
16	Power Transformer Electrical Parametric Data for One-Megawatt Systems	77
17	Power Transformer Parametric Data for Two-Megawatt Systems	78
18	Power Transformer Parametric Data for Five-Megawatt Systems	79
19	Power Transformer Weight Summary	86
20	Power Transformer Volume Summary	87
21	Predicted Characteristics of Silicon Diodes	98

LIST OF TABLES
(continued)

Table	Title	Page
22	Silicon Diode Rectifier for 500 Kilowatt System	99
23	Silicon Diode Rectifier for One Megawatt System	100
24	Silicon Diode Rectifier for Two Megawatt System	101
25	Silicon Diode Rectifier for Five Megawatt System	102
26	Gas Tube Diode Rectifier for One Megawatt System	103
27	Rectifier Diode Arrangement	108
28	Silicon Diode Rectification Systems	115
29	1.0 Megawatt Silicon Diode and Gas Diode Rectification Systems	111
30	Output Filters for 500 Kilowatt and 1.0 Megawatt Transistor Converters	121
31	Output Filters for Two Megawatt and 5.0 Megawatt Transistor Converters	122
32	Output Filters for 500 Kilowatt and 1.0 Megawatt SCR Converters	123
33	Output Filters for Two Megawatt and 5.0 Megawatt SCR Converters	124
34	Output Filter Weights and Volumes for Transistor Converters	131
35	Output Filter Weights and Volumes for SCR Converters	132
36	Switchgear Ratings	141
37	Summary of Drive Amplifier Components	145
38	Drive Amplifier Electrical Parameters	149

LIST OF TABLES
(continued)

TABLE	Title	Page
39	Drive Amplifier Weights and Volumes	156
40	Drive Amplifier Weight Variation With Frequency	158
41	Frequency Reference Oscillator Electrical Parameters	167
42	Frequency Reference Oscillator Weight and Volumes	171
43	Total Weights and Volumes of Control Package	173
44	Voltage Regulator Electrical Parameters	183
45	Voltage Regulator Weights and Volumes	185
46	Current Protection Circuit Electrical Parameters	190
47	Current Protection Circuit Weights and Volumes	193
48	Weight Summary	197
49	Volume Summary	198
50	Efficiency Summary	199

SECTION I
INTRODUCTION

INTRODUCTION

The earlier work on NASA Contract NAS5-1234 was concerned with a-c to d-c power conditioning equipment using a nuclear reactor and a turbo-generator as the electric energy source. The effort on Amendment 6 of this contract is devoted to static d-c to d-c converters that provide electrical power to ion propulsion systems from a nuclear-thermionic source. The most promising d-c to d-c converters are analyzed and parametric data is developed to investigate the size, weight, efficiency, coolant temperatures and coolant flow rates for the individual functional blocks that make up a d-c to d-c converter.

The specific converters analyzed are defined in Contract NAS5-1234, Amendment 6. The input voltages, output voltages, and power levels are as follows:

Input voltages: 20, 100, 300 and 600 volts

Output power and voltages:

500 kw at 5,000 volts

1,000 kw at 5,000 volts

2,000 kw at 20,000 volts

5,000 kw at 600 and 5000 volts with provisions for operation at either voltage.

Converters using several combinations of the above voltages and power levels are investigated and the results are presented in the following sections of this report.

SECTION II
PRELIMINARY DESIGN

PRELIMINARY DESIGN

The preliminary converter design establishes guidelines to expedite and direct study efforts. A functional block description is presented to identify and describe the circuits and functions of each functional block.

A. Guidelines

1. The study presents parametric data only for the functional blocks which make up the d-c to d-c converters. Circuit selection is based on minimum weight converter systems. The study does not present detailed design information or outline drawings. All other system equipment is excluded.
2. Efficiency, size, weight, coolant temperature, coolant flow rates, etc., are presented for each of the functional blocks of the d-c to d-c converter for the different input voltages and different power output ratings.
3. The interconnecting conductors between the converter functional blocks are not considered in this study.
4. Conductor losses within the functional blocks are not considered.
5. Conductor weight is assumed to be 5% of the functional block weight.
6. Fluctuation of source voltage due to sputtering in the thermionic diodes is not considered. The input filter is based only on the requirements of the inverter circuits.
7. The parametric data is based on engineering estimates of the characteristics of electrical components and materials available five years in the future. The availability of components and materials five years hence is estimated on normal industry progress or government funded programs and does not recognize crash development programs.
8. The parametric data is based on the following cooling systems:

Design:	Components mounted directly to cold plates having cooling tubes as integral parts.
Cooling Tubes Material:	Columbium and Beryllium
Cooling Fluid:	Eutectic NaK
9. Effects of nuclear radiation have not been considered. It is assumed shielding is provided as necessary to protect semiconductors from nuclear radiation. The amount of shielding required is not part of this study.
10. The electrical characteristics of the nuclear thermionic source was determined from the Pratt & Whitney Aircraft megawatt nuclear reactor space power plant shown reproduced in Figure 1.

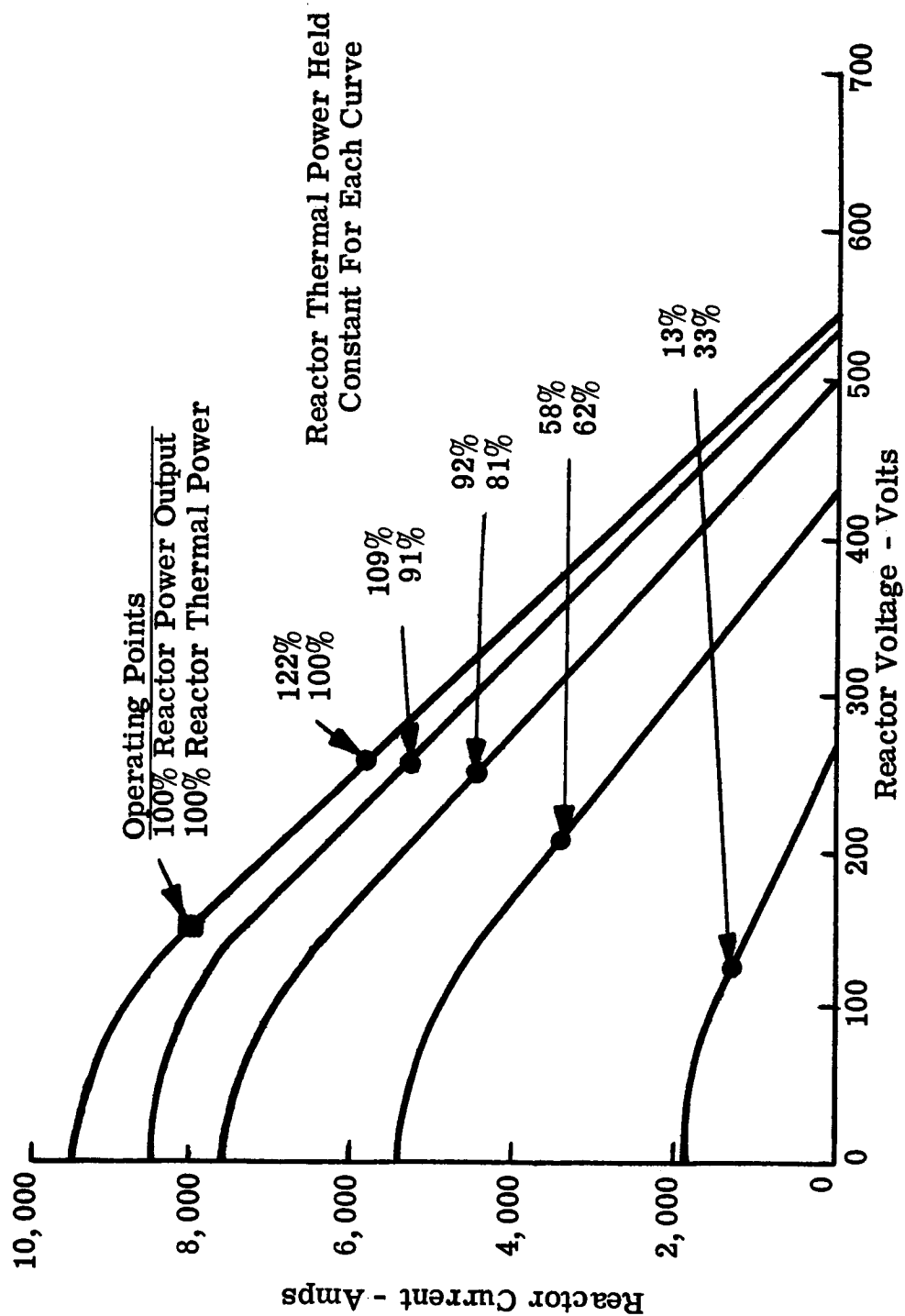


FIGURE 1
1 MW(e) Nuclear Thermionic Space Powerplant
Reactor Electrical Characteristics

Pratt & Whitney Aircraft

B. FUNCTIONAL BLOCK DESCRIPTION

Fundamentally, the conversion of relatively low d-c voltages to higher magnitudes involves power switching circuits which alternately interrupt the flow of d-c current. These circuits provide square wave voltages which are stepped up in magnitude by transformers and then converted to the d-c voltage by output rectifier assemblies. To complete the d-c to d-c converter systems, a frequency reference, drive amplifiers, voltage regulator, current protection, and filters must be included.

All of the converters are similar in concept although they differ in detail. Each system includes the primary power circuit and secondary control circuits. A block diagram of the basic d-c to d-c converter system is shown in Figure 2. The following paragraphs describe the circuits and functions of each block in Figure 2. Tabulated data is presented to aid in the selection of the circuit configuration to be used in the parametric data study.

Inverter

The function of the inverter is to convert the d-c power from the nuclear-thermionic source to a-c power. A-C is necessary to step up the voltage level through the use of transformers.

D-C to a-c inversion can be accomplished by any of several known circuits, both single phase and multi-phase. The choice of the best circuit depends on the specific application.

For spacecraft propulsion applications, the best circuit results in minimum propulsion system weight. This does not necessarily mean that the lightest inverter is best, because parameters of other system components are dependent on the type of inverter circuit used.

The weight of the following system components must be considered when selecting the inverter to be used.

1. Reactor system weight is influenced by losses in the power conditioning equipment.
2. The weight of the thermal radiator for cooling power conditioning equipment is influenced by losses in the equipment, and is very sensitive to operating temperature of the equipment.
3. The total weight of the power transformers depends on the kva rating of individual units, and on the operating frequency of the inverter.

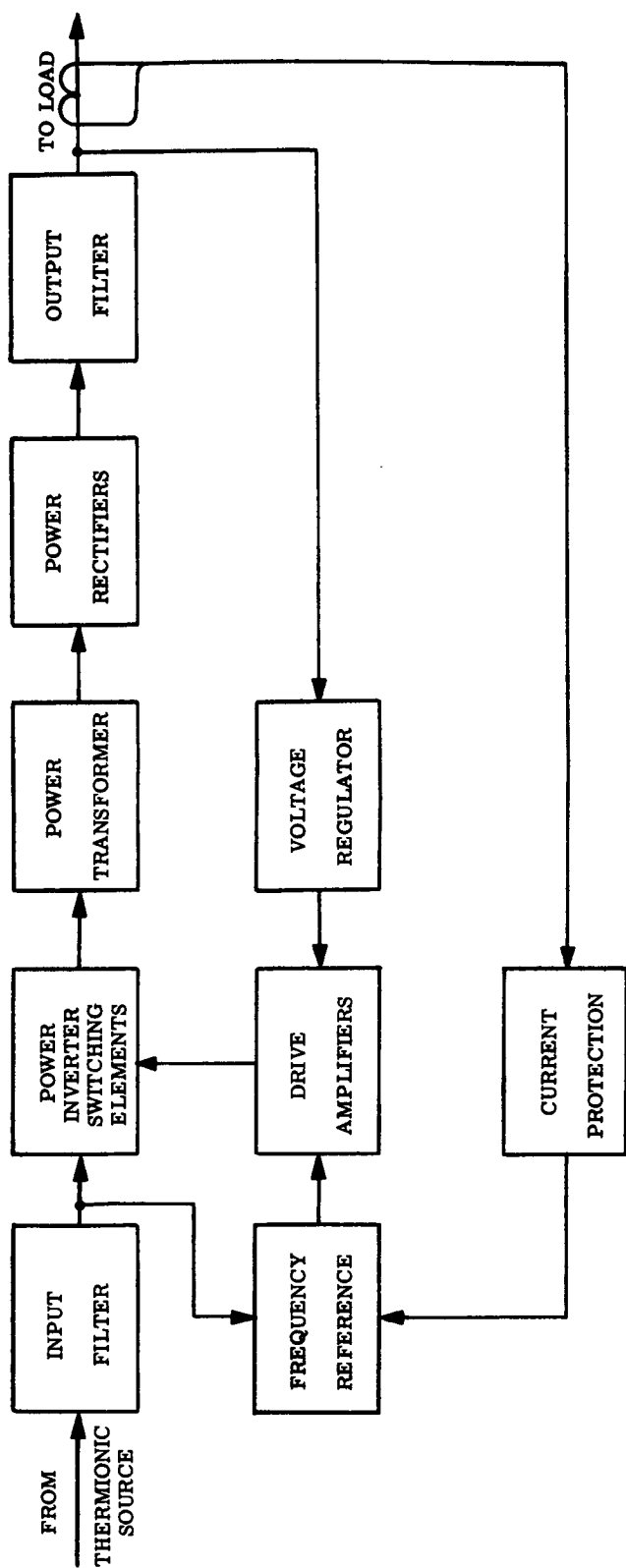


FIGURE 2
DC to DC Converter Block Diagram

4. The total weight of the commutating capacitors, for a given input power, is proportional to turn-off time of the switching elements used in the inverters.
5. The output filter weight depends on the frequency and magnitude of the ripple voltage produced by the inverters.
6. The input filter weight depends on the switching speed of the inverter switching elements, and the source impedance.

The various inverter circuits suitable for this application are shown in Figure 3. A quantitative comparison between them is required to choose the best circuits. Table 1 summarizes the calculated weights and losses of the major elements of the various circuits, and their effects on the weights of the thermal radiators, reactor system, and filters.

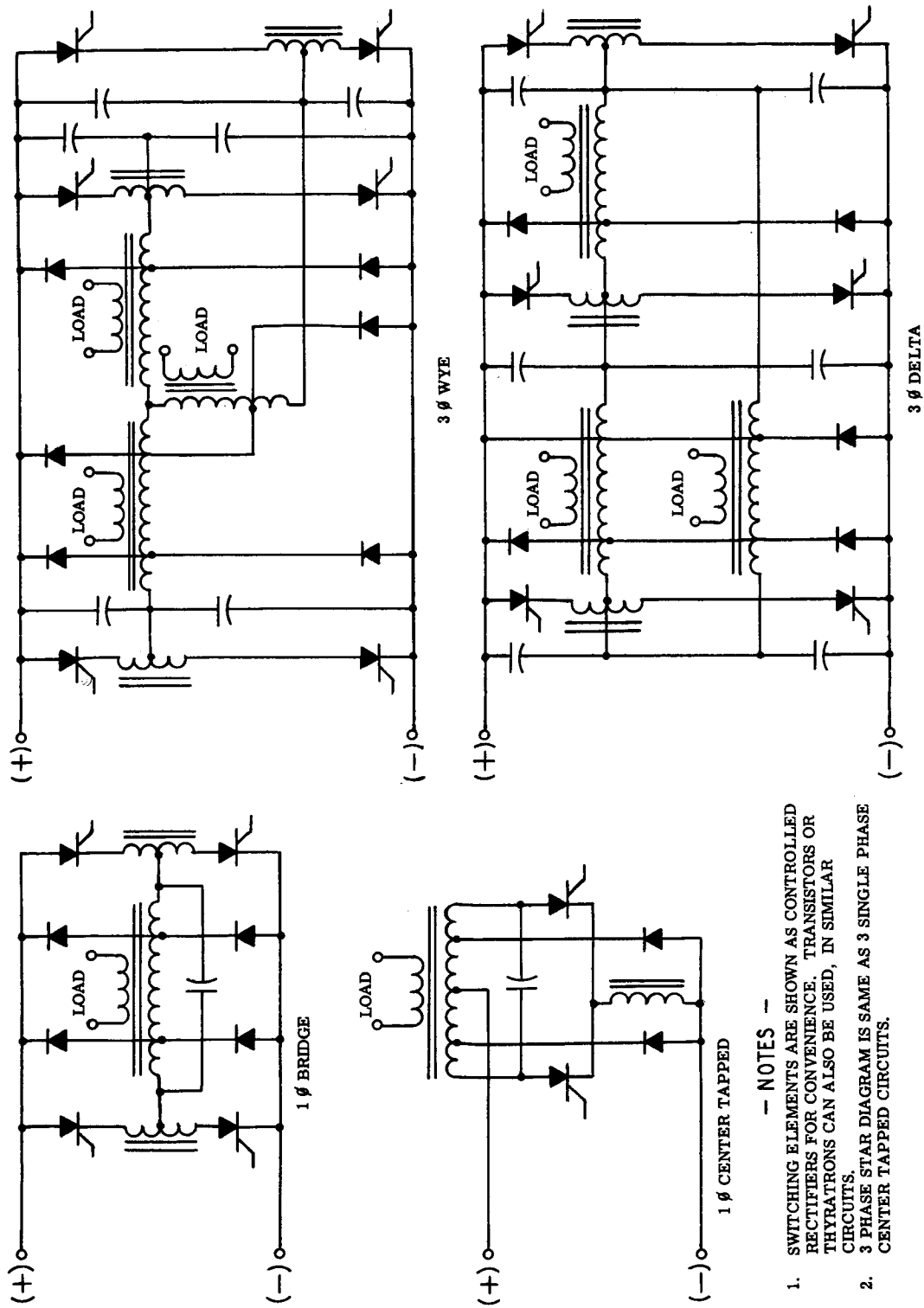
The figures in Table 1 are based on a 1000-kw system for an input of 100 volts d-c with an output of 5000 volts d-c and the use of silicon transistors and controlled rectifiers as switching elements. High temperature vapor-tube thyratrons are considered during a later portion of this study. The numbers are the result of preliminary calculations and are not intended to represent complete designs. However, they are sufficiently accurate to show the relative merits of the various circuit types.

The reactor weight penalty was chosen to be 8.6 lb/kw.¹ The radiator weight penalties are computed from the curve of Figure 4 which is a log-log plot of data received from NASA and incorporated in Westinghouse Report "Space Electric Power Systems Study", final report Vol. 3, dated November 1961 through December 1962. This report was prepared during an earlier part of Contract NAS5-1234. The curve is plotted on log-log paper to enable linear extrapolation to lower temperatures.

The data in Table 1 shows that minimum system weight results from using a single phase center-tapped transistor circuit as the basic building block for the inverter. A large number of individual circuits are required to reach the 0.6-to 5-megawatt power levels. This is true regardless of the circuit used, since none of them can carry the full power by itself.

For input voltages of 20 and 100 volts, the single-phase, center-tapped transistor circuit forms the basis for the parametric data developed in this study. At higher levels of input voltages this circuit is not used because the voltage rating of the transistor is exceeded.

1. Pratt & Whitney Report PWA-2107, Vol. II, Appendix 2. July-September 1962, NASA Contract NAS W-360.



- NOTES -

1. SWITCHING ELEMENTS ARE SHOWN AS CONTROLLED RECTIFIERS FOR CONVENIENCE. TRANSISTORS OR THYRATRONS CAN ALSO BE USED, IN SIMILAR CIRCUITS.
2. 3 PHASE STAR DIAGRAM IS SAME AS 3 SINGLE PHASE CENTER TAPPED CIRCUITS.

FIGURE 3
Inverter Circuit Schematic Diagrams

TABLE 1
COMPARISON AMONG SEVERAL POSSIBLE INVERTER
CIRCUITS

Relative Values for Equal Input Voltage (V) and Current (I)

Circuit Type	1 \emptyset Center Tap	1 \emptyset Bridge	1 \emptyset PWM	3 \emptyset Y-Y	3 \emptyset Δ -Y	3 \emptyset Δ - Δ	3 \emptyset Star - Y
No. Switching Elements Per Circuit	2	4	4	6	6	6	6
No. Capacitors per Ckt.	1	1	4	6	6	6	3
Capacitor Value	C/4	C	C	C/2	C/2	C/2	C/4
Capacitor Voltage	2V	V	V	V	V	V	2V
Total CV ² per Circuit	1	1	4	3	3	3	3
Total Capacitance	C/4	C	4C	3C	3C	3C	3/4C
Transformer Type	C.T. Primary	2 wdg.	2 wdg.	5 leg E core	E core	E core	5 leg E core
Relative Transformer Rating	1.00	1.00	1.00	1.06	1.00	1.00	1.06
Switching Element Current							
Peak	I	I	I	I	I	I	I
Average	I/2	I/2	I/2	I/3	I/3	I/3	I/3
RMS	I/2	I/2	I/2	I/2	I/2	I/2	I/2
Relative Filter Weight	1	1	1	0	1/3	1/3	0
Operating Voltage of Switching Element	2V	V	V	V	V	V	2V

TABLE 1 (continued)

CALCULATED WEIGHTS AND LOSSES FOR 1MW SYSTEM

Silicon Controlled Rectifier Circuits

Circuit Type	1Ø Center Tap	1Ø Bridge	1Ø PWM	3Ø Y-Y	3Ø Δ-Y	3Ø Δ-Δ	3Ø Star-Y
Transformer Loss (kw)	20.8	18.4	18.4	27.7	28.6	28.6	30.0
Switching Element Loss (kw)	17.6	30	30	33.8	33.8	33.8	33.8
Operating Frequency (cps)	800	800	800	800	800	800	800
Transformer Weight (lbs)	662	565	565	536	524	524	638
Output Filter Weight (lbs)	250	250	250	0	90	90	0
Capacitor Weight (lbs)	545	545	2180	1635	1635	1635	1635
Radiator Weight (lbs)	580	900	900	878	878	878	878
for Switching Elements							
Reactor Weight Penalty (lbs)	330	416	416	528	520	520	538
(8.6 lbs/kw loss)							
Transformer Radiator Weight (1 lb/kw)	21	18	18	28	27	27	30
Total of Above Weights (lbs)	2388	2694	4329	3605	3674	3674	3719

Input Voltage = 100 volts d-c
Output Voltage = 5000 volts d-c

TABLE 1 (continued)

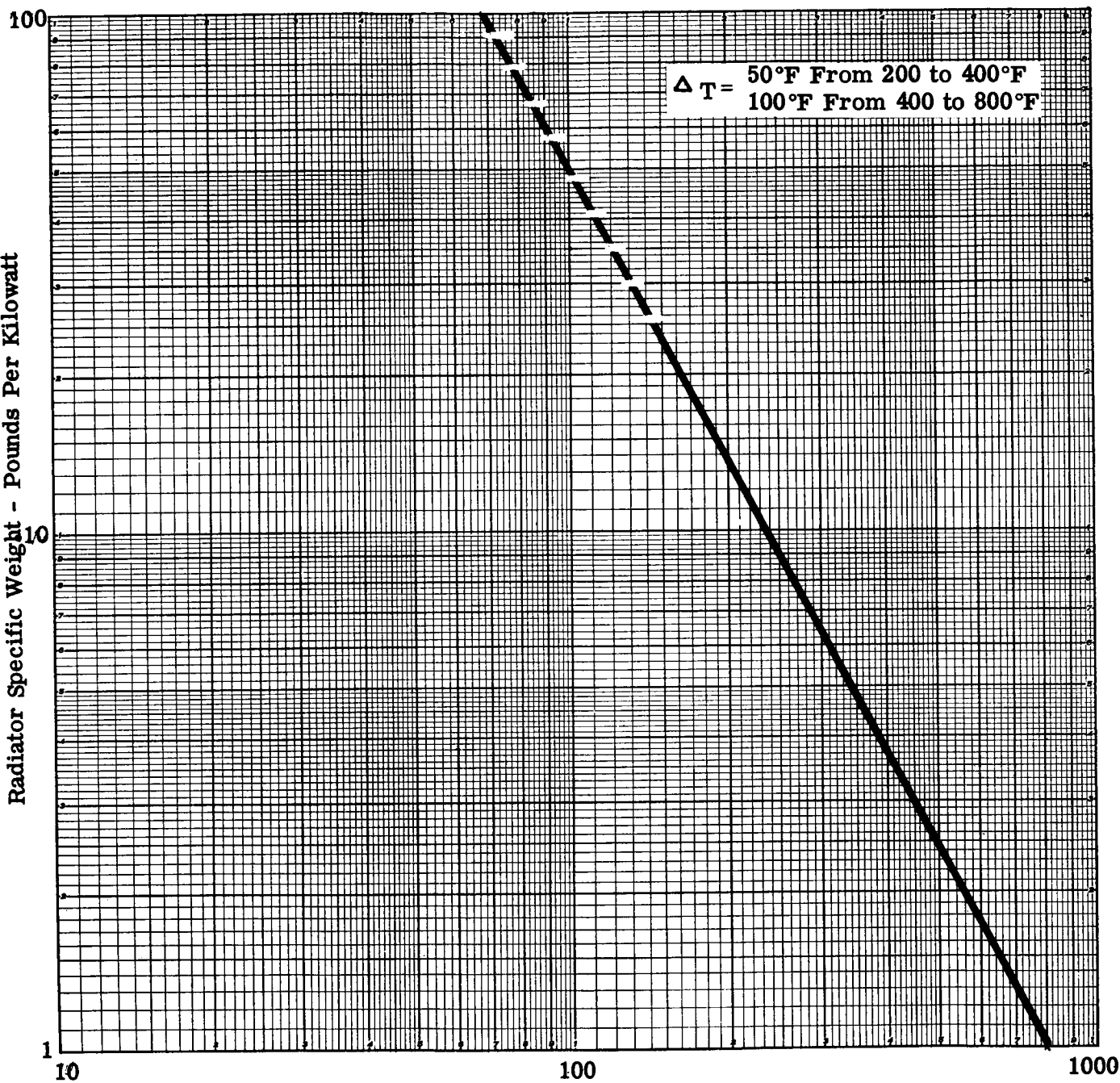
CALCULATED WEIGHTS AND LOSSES FOR 1MW SYSTEMS

Silicon Transistor Circuits

Circuit Type	1Ø Center Tap	1Ø Bridge	3ØY-Y	Δ-Y
Transformer Loss (kw)	44.1	39.0	63.6	56.3
Switching Element Loss (kw)	21.1	40.0	43.8	43.8
Operating Frequency (cps)	1250	1250	1250	1250
Transformer Weight (lbs)	196	196	0	71
Output Filter Weight (lbs)	119	119	357	357
Capacitor Weight (lbs)	217	400	416	416
Radiator Weight for Switching Elements Only (lbs)	586	500	556	464
Reactor Weight Penalty (lbs)	560	680	925	861
(8.6 lbs/kw loss)				
Transformer Radiator Weight (1 lb/kw)	44	39	64	56
Total of Above Weights (lbs)	1722	1934	2318	2225

Input Voltage = 100 volts d-c
Output Voltage = 5000 volts d-c

Radiator Specific Weight - Pounds Per Kilowatt



Average Coolant Temperature - °F

FIGURE 4

Radiator Specific Weight W_s .
Average Coolant Temperatures

The single-phase, center-tapped controlled-rectifier circuit is used for input voltages of 300 and 600 volts, because it is expected that development of controlled rectifiers will yield sufficiently high voltage ratings by the year 1968.

Three-phase circuits are not used in the study, because Table 1 shows that three phase systems are significantly heavier than single phase systems. This is due to the larger number of commutating capacitors and the higher losses in the three phase circuits.

Power Transformer

There are several single-phase and multiphase transformer designs which can be used in d-c to d-c converter systems. The selection of the single-phase transformer for use in the parametric study is dictated by the choice of the single-phase inverter circuit.

The function of the power transformer is to step up the voltage level of the a-c square waves produced by the inverter, to a level which provides the desired d-c output voltage after rectification. The basic transformer configuration consists of a single-phase cores with the number of separate primary windings equal to the number of inverter stages. The secondaries consist of an equal number of separate windings or a single common secondary winding for a group of cores. This arrangement provides current division in the inverter stages.

Power Rectifier Assembly

The function of the power diodes of the rectifier assembly is to convert the a-c square wave voltage of the power transformer secondaries into the desired d-c output bus voltage. As in the case of the power transformer, the selection of single phase rectification is dictated by the choice of the single phase inverter circuit. The possible circuits for this application are the single-phase, full-wave bridge rectifier and the single-phase, center tapped full wave rectifier. Both circuits require the same number of diodes. However, the full wave bridge rectifier uses a smaller power transformer for the same d-c power delivered to the load. Therefore, this circuit is preferred and selected for parametric study. Where conditions permit, ceramic-body, high-temperature, gas-tube diodes are used as the rectifying element. In all other instances silicon diode semiconductors are used.

Output and Input Filters

The function of the output filter is to reduce the ripple voltage on the d-c output bus to a value compatible with the load requirements. The output filter also aids in protecting the rectifiers and inverter switching elements from voltage surges that may appear on the load bus. The filtering requirement is dependent

on the inverter circuit, inverter switching frequency and the type voltage regulation employed. The parametric study is based on a conventional low-pass L-C filter that maintains the output ripple voltage below 4 percent RMS for resistive loads.

The function of the input filter is to supply energy during the initial part of the inverter commutating interval and absorb energy during the latter part of the commutating interval, maintaining a smooth d-c voltage on the input bus. This filter also aids in reducing any voltage surges caused by sputtering in the thermionic source. The input filter is a capacitor and is physically located at the input to the inverter.

Frequency Reference and Drive Amplifier

The frequency reference determines the operating frequency of the power inverter circuits and generates a square-wave voltage that is amplified by the drive amplifier. The output of the drive amplifier provides a common drive signal for the inverters. Thus the power inverters all switch at the same frequency and operate in phase with each other.

The frequency reference consists of a self-starting transistor oscillator whose frequency is proportional to its input voltage. Since the input voltage comes from the main d-c bus, the oscillator generates a frequency proportional to this bus voltage. This variable frequency is desirable because it prevents saturation of the inverter power transformers if the input bus voltage rises.

The drive amplifier consists of a semiconductor switching circuit that provides an a-c square wave at the correct voltage and current to drive the inverters. The design resembles that of an inverter circuit, except the output transformer provides a low output voltage.

Voltage Regulation

A voltage regulator is required to assure constant voltage output from the power conditioning equipment. Without it, changes in load or reactor temperature would cause output voltage variations. The required voltage regulation is assumed to be ± 5 percent.

There are two techniques normally used for voltage regulation in this type of equipment. They are pulse-width-modulation, and phase shift regulation. Both of these techniques have the disadvantage of distorting the square wave output. This distortion requires heavier filters than are necessary if the output is an undistorted square wave.

The regulation technique proposed for this study overcomes this disadvantage. Regulation is achieved by turning off an appropriate

number of of power inverter stages when the output voltage starts to rise. Each stage that is turned off subtracts from the output an increment of voltage approximately equal to the amount it formerly added. Thus, the voltage regulation is similar to the tap-changing technique used on electric utility systems. The method of interconnection of the inverter circuits allows a stage to be turned off simply by removing its drive signal.

The voltage regulator consists of a reversible counter, with appropriate control and amplifier circuits. When output voltage begins to rise above the allowable maximum, the counter starts to count. For each count, a single power-inverter stage is shut down by a semiconductor switch that shorts the inverter's drive signal. The process continues until the output voltage has been returned to its correct value. When the output voltage drops below the specified minimum value, the counter reverses and restarts the inverter stages one at a time, until the voltage is returned to normal.

Current Sensing and Protection

The function of the current sensing and protection circuit is to protect the power conditioning equipment from damage if a load bus fault occurs.

For a minimum weight system, it is necessary that the power conditioning equipment be required to carry a minimum of overload current. The weight of commutating capacitors increases rapidly with increasing overload capability. To minimize both the magnitude and the time duration of overload currents the following means of current sensing and protection is proposed.

The secondary current of the power transformers is monitored by a current transformer working into a bistable switch. When the current exceeds a predetermined value the bi-stable switch changes states, emitting two simultaneous signals. One signal opens the main circuit breaker to interrupt input current. The other signal stops the frequency reference oscillator. Stopping the frequency reference oscillator interrupts the drive to the inverters, thus causing the system to stop operating. This action takes place in much less time than required to open the main circuit breaker.

The necessity of opening the main circuit breaker is as follows: The inverters that utilize silicon controlled rectifiers will not stop in an open circuit condition when the drive is interrupted. Instead, they complete a half-cycle of operation and stop with half of the controlled rectifiers still conducting. The resulting high currents through the controlled rectifiers can be sustained for only a short time before the heat generated causes the junction temperatures to reach destructively high levels. The main breaker must open before this happens. It is expected that a circuit breaker of normal speed is sufficient for this purpose.

Switchgear¹

The 5-megawatt converter supplies considered in this study must provide their power output at either of two d-c output voltages, 0.6 or 5 kilovolts. The earlier work performed on NAS5-1234 shows that the best approach to provide step type output voltage variation is through a number of separate voltage sources which are switched from parallel, to combined series-parallel, to a total series configuration by a rectifier bank switch. This particular approach offers a means of working the rectifier banks at their designed rating and thereby providing the most efficient use of the rectifier assemblies.

With the preceeding in mind, the following basic approach has been selected for the converter systems with two output voltage levels. An 8 to 1 change in output voltage is accomplished by an all series or all parallel configuration of 8 isolated a-c sources working into 8 separate rectifier banks. The rectifier output is connected to 8 separate d-c filters before passing through the rectifier bank switch. Therefore, for this converter system the block diagram of Figure 2 would be modified by inserting the rectifier bank switchgear between the output filter and the load.

At 5 kilovolts all 8 rectifier banks are in series and each rectifier and filter assembly provides an output of 625 volts d-c. At 0.6 kilovolts all rectifier and filter banks are in parallel and each of the 8 assembly output voltages are reduced 25 volts by regulator action.

Since a power transformer is a necessary requirement in the voltage transformation of d-c to d-c converters, it also serves the additional function of providing the required voltage isolation of the a-c sources for the separate rectifier assemblies.

Cooling System Investigation

Prior to developing parametric data on a specific cooling system for the d-c to d-c converter electrical functional blocks, several different types of cooling systems were investigated. Table 2 presents the various cooling systems considered and lists the relative advantages and disadvantages of the various systems. The cold plate cooling system has the best qualities and is used in this study program. This cooling system uses a liquid coolant to transfer the heat from the electrical component cold plate to an external radiator.

1. By mutual agreement between NASA and Westinghouse, parametric data for the switchgear was not prepared. The only purpose of this study was to define the switchgear requirements. It has been assumed that the results of the NASA switchgear program (contract NAS3-2546) will provide information for the design of switchgear for this application.

TABLE 2

COMPARISON OF COOLING SYSTEMS USABLE IN SPACE

I. COLD PLATE COOLING WITH LIQUID COOLANT

Advantages

1. Centralized, compact structure
2. Most efficient cooling
3. Liquid metal systems are static

Disadvantages

1. Requires external radiator to dissipate heat
2. Radiator vulnerable to meteorites
3. Liquid metal systems are heavy
4. Requires pump.

II. FORCED CONVECTION

Advantages

1. If manned satellite, existing air conditioning could be used.
2. Probably most compact design
3. Probably lightest design

Disadvantages

1. Requires external radiator, heat exchanger and secondary cooling loop.
2. Requires fan and/or pump
3. Requires pressurized system

III. THERMOELECTRIC COOLING

Advantages

1. Provides lower operating temperature for higher ambient.

Disadvantages

1. Larger than other systems
2. Poor efficiency
3. Requires auxiliary cooling system

IV. CRYOGENIC COOLING

Advantages

1. Centralized design
2. No radiator needed
3. Not susceptible to meteorites
4. Just as efficient in cooling as cold plate
5. Can be completely static

Disadvantages

1. Not feasible for long mission durations
2. Requires pump or intricate moving parts
3. Coolant weighs more than radiator for long duration missions

V. DIRECT COMPONENT RADIATION

Advantages

1. No external radiator needed
2. No coolant needed
3. Less overall weight (no pump, coolant, etc.)

Disadvantages

1. Highly susceptible to meteorites
2. Difficult mounting problems
3. In high power equipment, leads will be long and inefficient

TABLE 2 (continued)

COMPARISON OF COOLING SYSTEMS USABLE IN SPACE

VI. POWER REFRIGERATION SYSTEM

Advantages

1. Lower component operating temp.
2. Less coolant and smaller pump needed
3. Probably lighter construction

Disadvantages

1. Requires external radiator
2. Not static

From Table 2, it is not immediately obvious why the cold plate system was selected. The best way to approach the method of selecting a system is not to look at the merits of the cold plate system but rather the disadvantages of the other systems which preclude the possibility of their use at this time. In each section of Table 2 the disadvantage that is most detrimental to that particular system is underlined.

It appears that at least two of the systems have future possibilities for space static cooling systems. Thermoelectric cooling is a field where research may provide the means for better static cooling systems in the future. Present day components, with low operating temperatures, could be mounted on a thermoelectric cooler. The cooler would pump the heat from the component to a higher temperature allowing a hotter coolant and hence a smaller radiator. At present the thermoelectrics are too inefficient for use. Another system that is more efficient than the thermoelectric is power refrigeration. This system is rejected because it is not static. A static gas type refrigeration cycle cannot be used because it is dependent on gravity for its proper functioning.

The direct radiation method is also feasible except for the problems involved in launching a vehicle with all the equipment mounted externally. If some type of folding or expanding mounting brackets could be developed, the direct mounting would probably be the lightest system.

Coolant Investigation - In Section IV of Volume I of the Final Report of the Space Electric Power Systems Study Contract NAS5-1234, dated November 1961 through December 1962, an analysis of cooling fluids and system cooling was made. The part of this analysis pertaining to coolants is applicable to this present study. The fluids most desirable for design purposes were found to be MIPB, OS-124, and NaK. Since the contract prefers use of liquid metal, for compatibility with an EM pump, the coolant fluid used in this study is eutectic NaK.

Finding the proper metal for use as coolant carrying tubes in a system which utilizes electric components ranging in operating temperature from 90°C to 600°C presents numerous problems. In the high temperature range there is little choice of material. The only liquids which are radiation resistant and will stand 600°C temperature are liquid metals. The presently known materials which are compatible with liquid metals at this temperature are columbium, nickel, and stainless steel. Because of its higher thermal conductivity and its retention of strength at 600°C, columbium is used as the coolant tube material for this application. At temperature ranges up to 200°C where liquid metal is less corrosive, beryllium, which is a lighter material than columbium, is used. Although beryllium is somewhat brittle, better metallurgical techniques should improve it in the next five years. Beryllium can be used, with the proper design, in its present

state. Another reason for selecting beryllium is that its coefficient of thermal expansion is similar to that of columbium. Considering a liquid metal loop incorporating electrical components, an EM pump, and the external radiator, the coefficient of thermal expansion must not differ significantly for the different metals used. Another problem in a closed loop of this type is that of mass transfer by the liquid metal. Columbium is used at high temperature because of its resistance to mass transfer. At low temperature beryllium should resist this action. Little or no information is available on the joining of columbium and beryllium. With the current progress being made in the joining of dissimilar metals, this problem should be overcome in the next five years.

Where possible and practical, aluminum or magnesium is used for the structure. In some cases, as in high temperature areas, aluminum or magnesium will not retain enough strength. In these cases columbium is used for structure as well as for the cooling tubes.

Physical Design - The physical design of the cooling system can vary with the mission of the equipment. Designs based on minimum weight and volume differ from designs based on maintainability. The cooling system design strives for the lightest, most compact overall package.

A system using a liquid as the heat transfer medium must be liquid tight. This implies that each module will have to be drained before it can be removed for maintenance. A double plate system of mounting could be used where the cold plate would contain cooling tubes and another plate, on which components would be mounted, would be bolted to the cold plate. This system adds approximately one quarter more weight to the system. The lightest construction then, would be to mount components directly to a plate containing cooling tubes. Individual components can be removed but it will not be possible to remove an entire module without draining the system and disconnecting cooling tubes.

SECTION III
FUNCTIONAL BLOCK ANALYSIS

FUNCTIONAL BLOCK ANALYSIS

The analysis of each functional block consists of a description, design criteria, parametric data, a discussion of problem areas and an analysis of data and recommendations. This information is contained in separate reports for each functional block. This arrangement allows each section of the converter to be examined independently in the same manner the study was performed.

Some of the parametric data presented are based on designs using materials that require research and development before practical equipment can be realized. The application of these materials are discussed in the functional block reports. The results of the NASA Materials Program, leading to advanced electric power systems, will provide applicable information for high temperature conductors, insulators and magnetic materials. Industry is presently engaged in this materials program under NASA Contract NAS3-4163.

A. INPUT FILTER

Input filters are necessary for the systems that use silicon-controlled rectifiers or vapor-tube thyratrons as the inverter switching elements, but not for the systems that use transistors. The difference results from the fact that transistors have an inherent ability to turn themselves off; whereas, controlled rectifiers and thyratrons require external turn-off circuits.

Electrical Design

Description

The filter consists of a number of capacitors, connected in parallel across the input terminals of the d-c to d-c converter. The capacitors are similar to the type utilized for inverter commutating purposes. They are made of aluminum foil with ML dielectric, enclosed in aluminum cans. The characteristics of this type of capacitor are shown in the "Inverter Switching Circuits" portion of this report, Table 8. Capacitors used for input filters range in value from 51 to 1140 microfarads with rated voltages up to 1200 volts. A fuse is in series with each capacitor to prevent failure of the filter in case a short circuit occurs within a capacitor. Fuses capable of operating in space environment will probably require development.

Operation

The input filter serves two functions during the commutating interval of the vapor tube or SCR inverter. During the first part of the commutating interval, the action of the commutating circuits causes the inverters to demand current in excess of the normal load current. The input filter supplies this surge. At the end of the first part of the commutating interval there is a certain amount of energy "trapped" in the commutating inductors. This energy is fed back to the power source during the second part of the commutating interval. It has been assumed that the thermionic diodes cannot accept power. Therefore, the filter must absorb the "trapped" energy.

Hence, the input filter capacitor discharges during the first part of the commutating interval, and charges during the second part. The value of filter capacitance depends on the characteristics of the thermionic source and the inverter, and is independent of frequency.

Design Criteria

1. The thermionic source cannot accept power, and therefore, the voltage across the source terminals, during commutation, may be allowed to reach but not exceed the normal open circuit source voltage.

2. The dynamic characteristic of the thermionic source is the same as its static volt-ampere characteristic.

In the interest of minimum weight, the smallest possible filter capacitance is used, consistent with the requirements of the inverter circuits. It may be that other considerations, such as thermionic diode heating due to ripple current, or suppression of radio frequency interference, would dictate larger values of capacitance, resulting in more filter weight.

Because input filters are not essential to the operation of the transistor inverters, no filters were calculated for the 20 and 100 volt systems.

Parametric Data

The electrical weights and heat losses of the input filters are summarized in Table 3, for the different inverter power ratings and frequencies. Typical variation of filter heat load with system power rating is shown in Figure 5, for a frequency of 1000 cycles per second.

Problem Areas

The major problem in evaluating input filters is the lack of precise information regarding the characteristics of the thermionic source. The previous two assumptions are made to provide a basis for design, but it is not known whether these assumptions are realistic.

Secondary to the above problem is the fact that exact solutions for filter capacitance and power loss are practically impossible to obtain analytically, and are best found experimentally. Since the experimental approach is impossible at this time, the filter values have been determined by approximate methods.

Analysis

The values of capacitance required for the input filters and the resulting weight and power losses are very dependent on the characteristics of the thermionic source. Since the source characteristics are not well defined at this time, particularly the dynamic characteristics, the filter parameters given in Table 3 are considered reasonable estimates, not accurate values. Relative values of the different filters are more meaningful than the absolute values of weight and losses.

Accurate determination of the absolute values of filter parameters is best accomplished by the experimental approach with actual equipment. The practical experimentation that has been done to date with non-thermionic power sources tends to indicate that the values of weight given in Table 3 are too low. However, no attempt was made in these experiments to minimize filter weight.

TABLE 3

INPUT FILTER ELECTRICAL PARAMETERS

Voltage Input (volts) Power Output (megawatts)	300 .5	300 1	300 2	300 5	600 .5	600 1	600 2	600 5	High Temp. 50 1
Number of Capacitors & Fuses	24	24	48	192	24	24	48	192	152
Capacitance of each (mfd)	102	204	204	128	51	102	102	64	1140
Rated Voltage (volts)	600	600	600	600	1200	1200	1200	1200	100
Total Capacitance (mfd)	2448	4896	9792	24,600	1224	2448	4896	12,300	173,000
Weight of each Capacitor (lbs)	18	34.5	34.5	22	16.6	33	33	21	8
Weight of each Fuse (lbs)	.5	.5	.5	.5	.5	.5	.5	.5	.5
Total Weight of Electrical Parts (lbs)	445	853	1682	4380	410	805	1610	4130	1296
Heat Loss at	9.6	19	38	94	4	7.4	14.9	36.5	27.4
50 cps (watts)	19.2	38	76	188	8	14.8	29.8	73	54.8
100 cps (watts)	38.4	76	152	376	16	29.6	59.6	146	109.6
200 cps (watts)	96	190	380	940	40	74	149	365	274
500 cps (watts)	192	380	760	1880	80	148	298	730	548
1000 cps (watts)	384	760	1520	3760	160	296	596	1460	1096
2000 cps (watts)	960	1900	3800	9400	400	744	1490	3650	2740

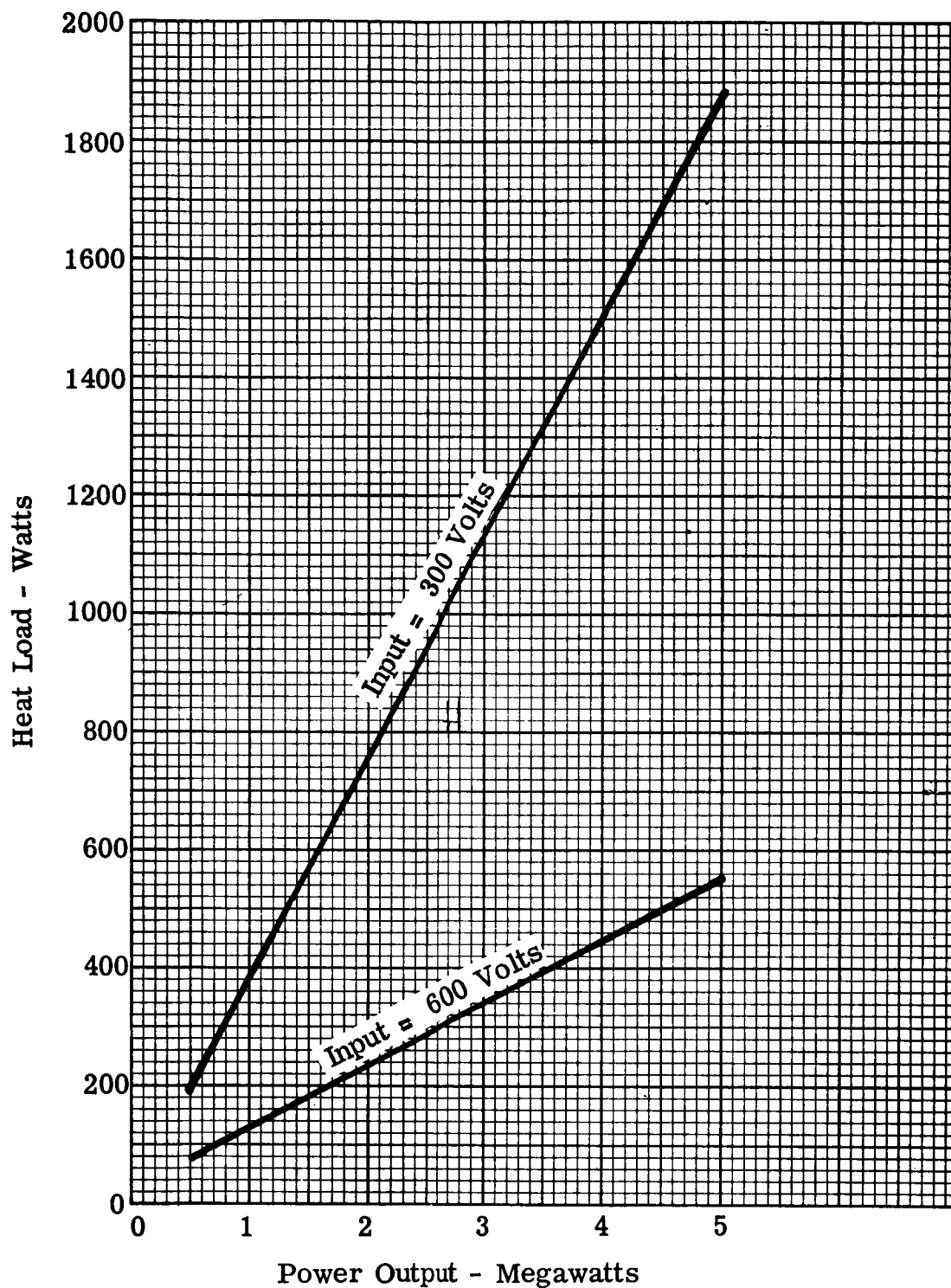


FIGURE 5
Input Filter
1000 Cycles Per Second
Heat Load Vs. Power Output

Recommendations

1. Evaluation of input filter parameters should be carried out by experimental means in advance of the time that flight hardware is specified.
2. Ways to reduce input filter weight should be investigated because the input filter amounts to a large fraction of the weight of the power conversion equipment. One method would be to operate several small power converters out of phase, from one common source, rather than one large unit.

Mechanical Design

Description

The cylindrical-shaped input filter capacitors are flange-mounted to support rails which are parallel to the capacitor centerlines. Cylindrical-shaped fuses are either clip or flange-mounted to the rails. Adhesive bonding may be used to reduce thermal resistance across mechanical joints.

Filter losses are low compared to other components in the converter system, and their surface area encourages cooling by direct radiation, provided that a compartment wall temperature is maintained at approximately 100°C. However, since such a mounting location is not provided, coolant conduits are assumed to be included, integral with the support rails, with cooling by direct conduction from the capacitor case to the coolant fluid. Coolant fluid is assumed to be eutectic NaK.

Design Criteria

The following basic design criteria were used to calculate the required parametric data.

1. The coolant was assumed to be eutectic NaK, which has a specific heat of 0.210 Btu/lbs.-°F, and a density of 0.0306 lbs/in.³. Convection temperature drop is 1°C.
2. Beryllium for use in coolant tubes and structure has the following characteristics:

Density	0.067 lbs/in. ³
Thermal Conductivity	87 Btu/hr-ft-°F
Thermal Expansion	6.4 x 10 ⁻⁶ in/in/oF
3. Adhesive bonding is .002 inch thick, with a thermal conductivity of 0.227 Btu/hr-ft-°F.
4. Minimum achievable thermal resistance between two surfaces not bonded together is 0.2°C/watt in a space environment.

5. Maximum capacitor operating temperature is 180°C for all designs. This is approximately equivalent to 25 per cent derating of the rated allowable temperatures. Coolant conduit wall temperature is 140°C.
6. Weight of cooling system and supporting structures is 30 per cent of the total weight.

Parametric Data

Input filter weights and volumes are presented in Table 4 for the 300- and 600-volt systems at power levels of 0.5, 1.0, 2.0, and 5.0 megawatts, and for the 50 volt, one megawatt high temperature system. Input filters are not required in the 20- and 100-volt transistor systems.

Variations of weight and volume with power rating are shown in Figures 6 and 7 respectively. Weights and volumes are constant within the frequency spectrum from 50 to 5000 cycles per second.

Variation of heat loads with power rating and input voltage is given in Figure 5. Figure 8 shows the variation of coolant-temperature rise with flow rate for heat load from one to 100 kilowatts which is absorbed by eutectic NaK coolant. From Figure 8, variation of coolant inlet temperature with flow rate may be determined for any assumed heat load and coolant conduit wall temperature. Based on an assumed wall temperature of 140°C, Figure 9 gives variation of coolant inlet temperature with flow rate for one-megawatt designs at an inverter switching frequency of 1000 cycles per second. The effect of inverter switching frequency on coolant inlet temperature is illustrated in Figure 10.

Problem Areas

1. A major problem area which requires development effort is in the use of beryllium for coolant tubes and support rails. Reliable techniques for forming and joining beryllium must be developed, as well as for joining beryllium to other metals which might be used in a complete power system cooling loop.
2. Development of reliable adhesive bonds is required for use in a space environment. It should be either sufficiently elastic to relieve thermal expansion differentials, or strong enough to resist thermal stresses created between materials of different relative expansions.

Analysis and Recommendations

From comparison of specific weights in Table 4, the 600-volt, one- and two-megawatt designs appear most attractive.

TABLE 4

INPUT FILTER WEIGHTS AND VOLUMES

Power Level (megawatts)	0.5	1.0	2.0	5.0
<u>300 Volt System</u>				
Total Weight (lbs)	665	1278	2550	6470
Total Volume (cu.ft.)	11.03	18.8	37.6	101.5
Specific Weight (lbs/kw)	1.330	1.278	1.275	1.294
<u>600 Volt System</u>				
Total Weight (lbs)	615	1206	2410	6200
Total Volume (cu.ft.)	11.03	17.7	35.4	97.1
Specific Weight (lbs/kw)	1.230	1.206	1.205	1.240
<u>50 Volt System - High Temperature</u>				
Total Weight (lbs)		1940		
Total Volume (cu.ft.)		23.0		
Specific Weight (lbs/kw)		1.94		

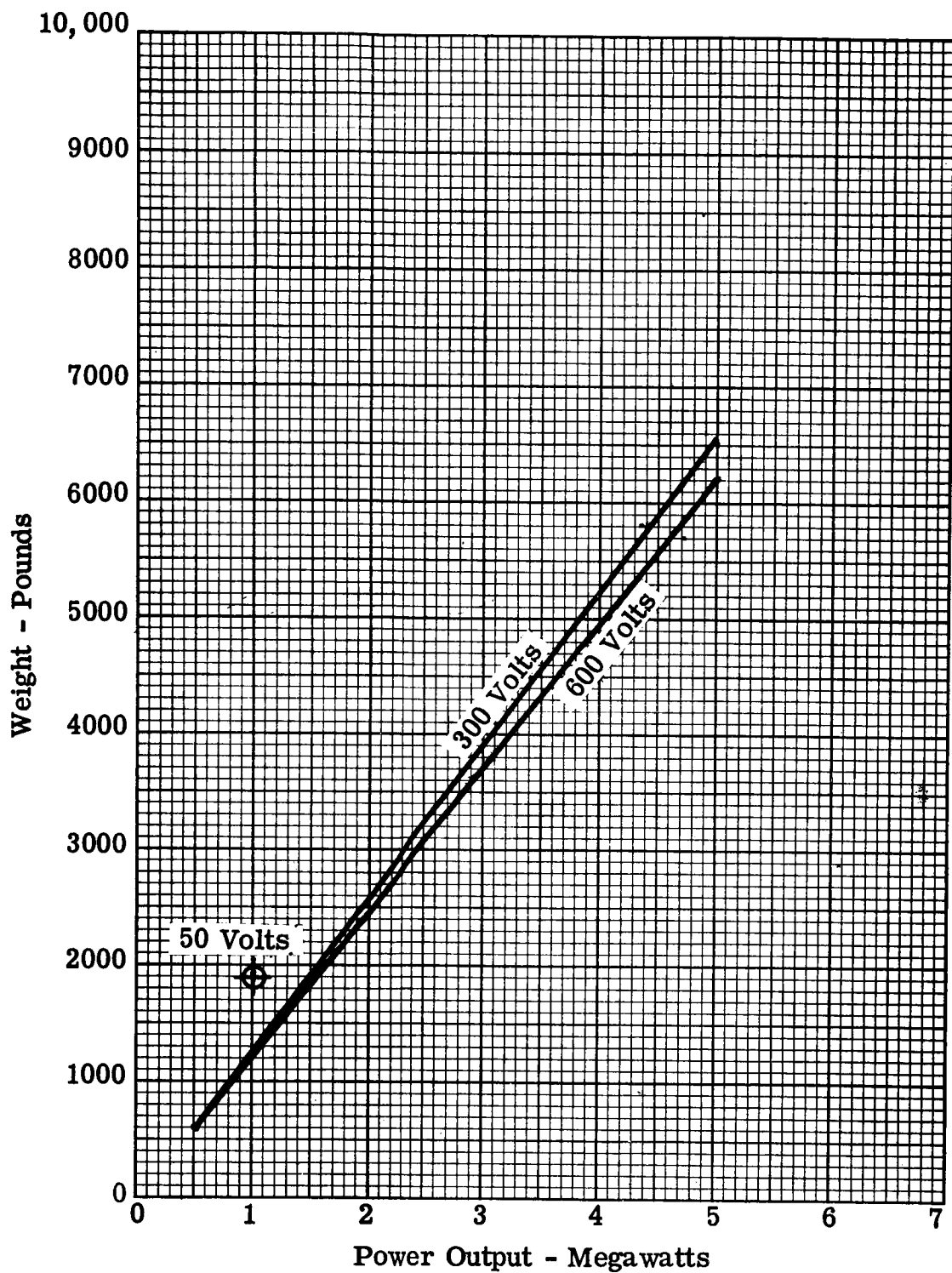


FIGURE 6
Input Filter
Weight Vs. Power Output

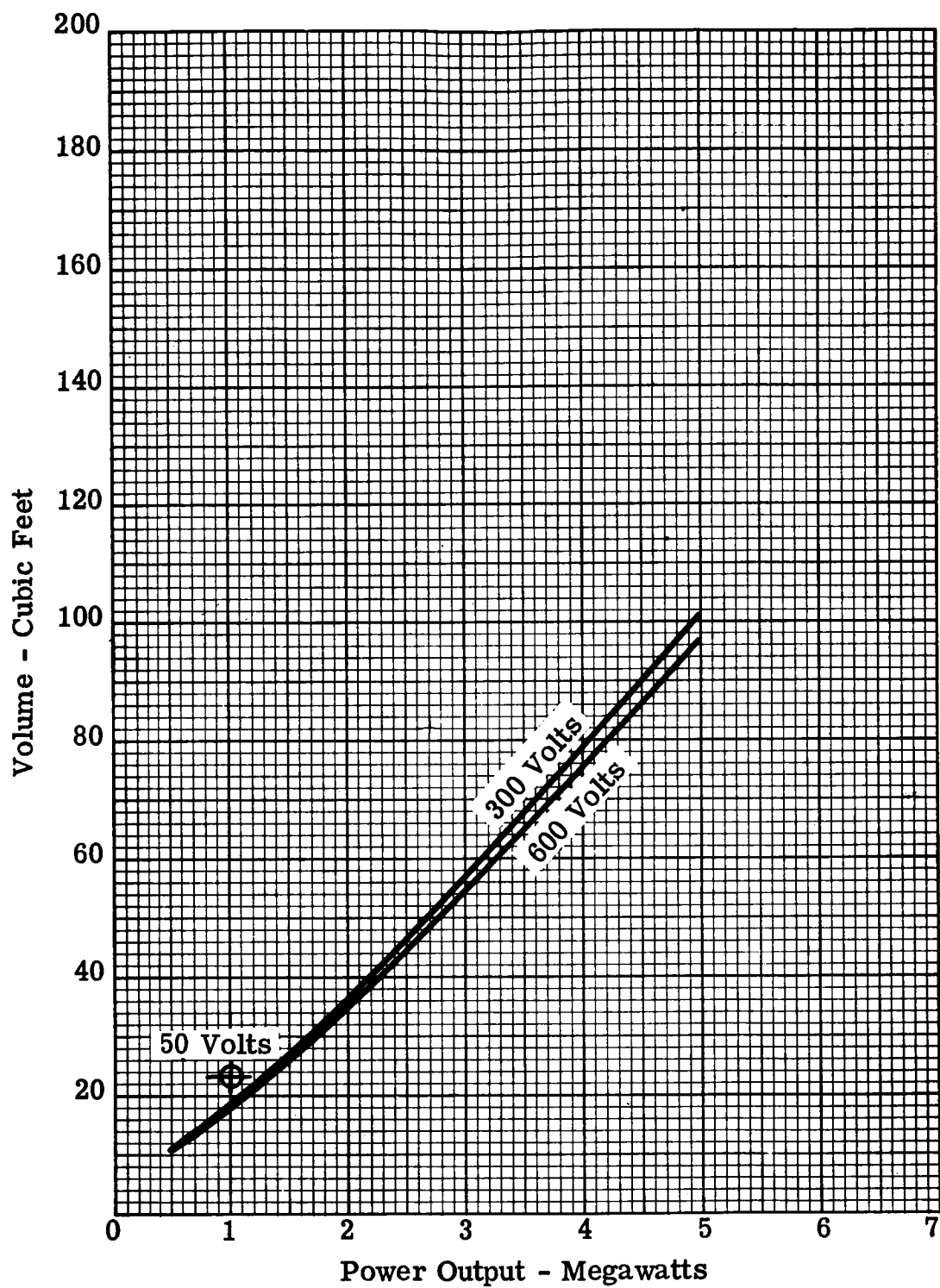
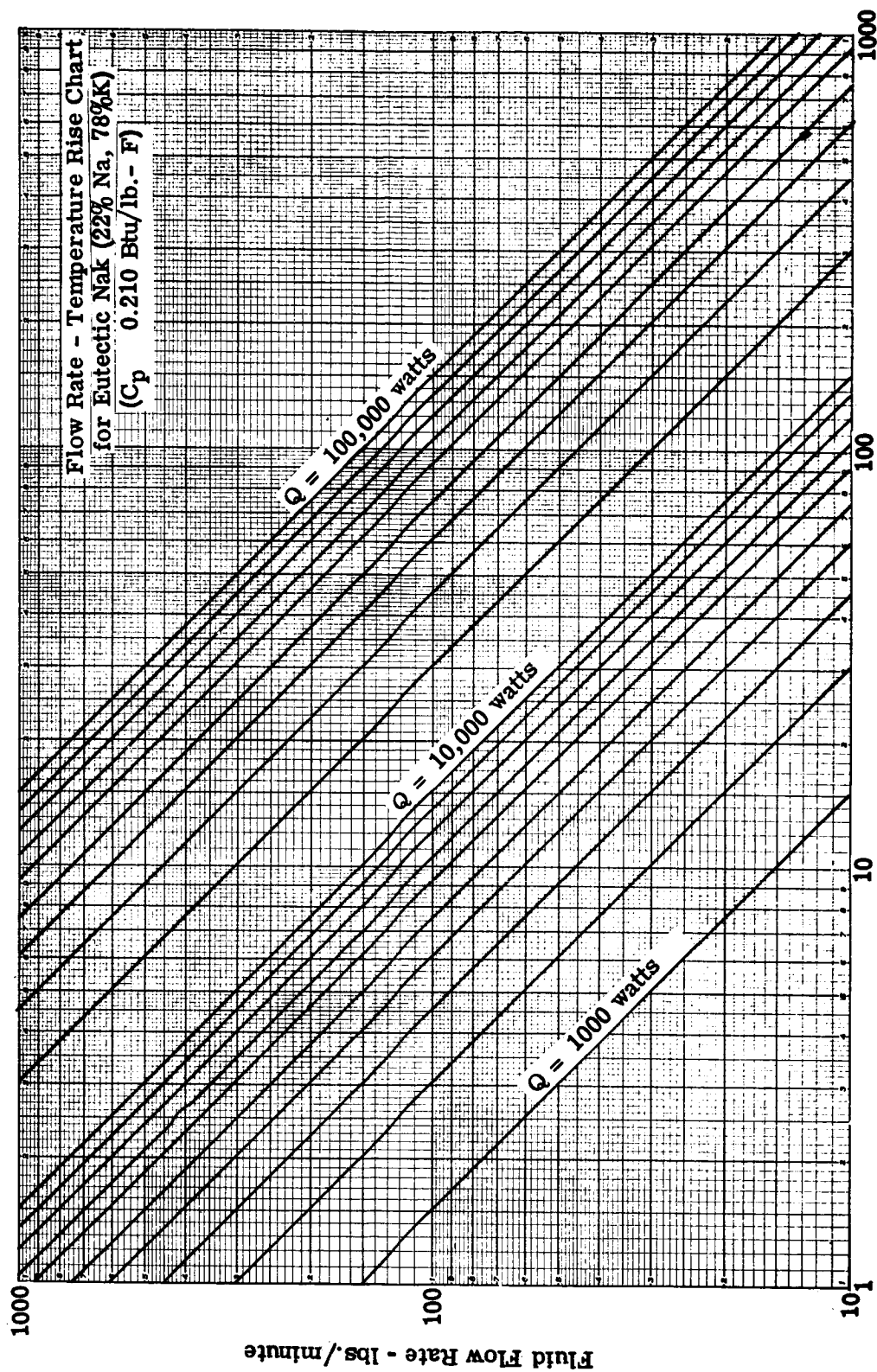


FIGURE 7
Input Filter
Volume Vs. Power Output



Fluid Temperature Rise - Degrees Centigrade

FIGURE 8

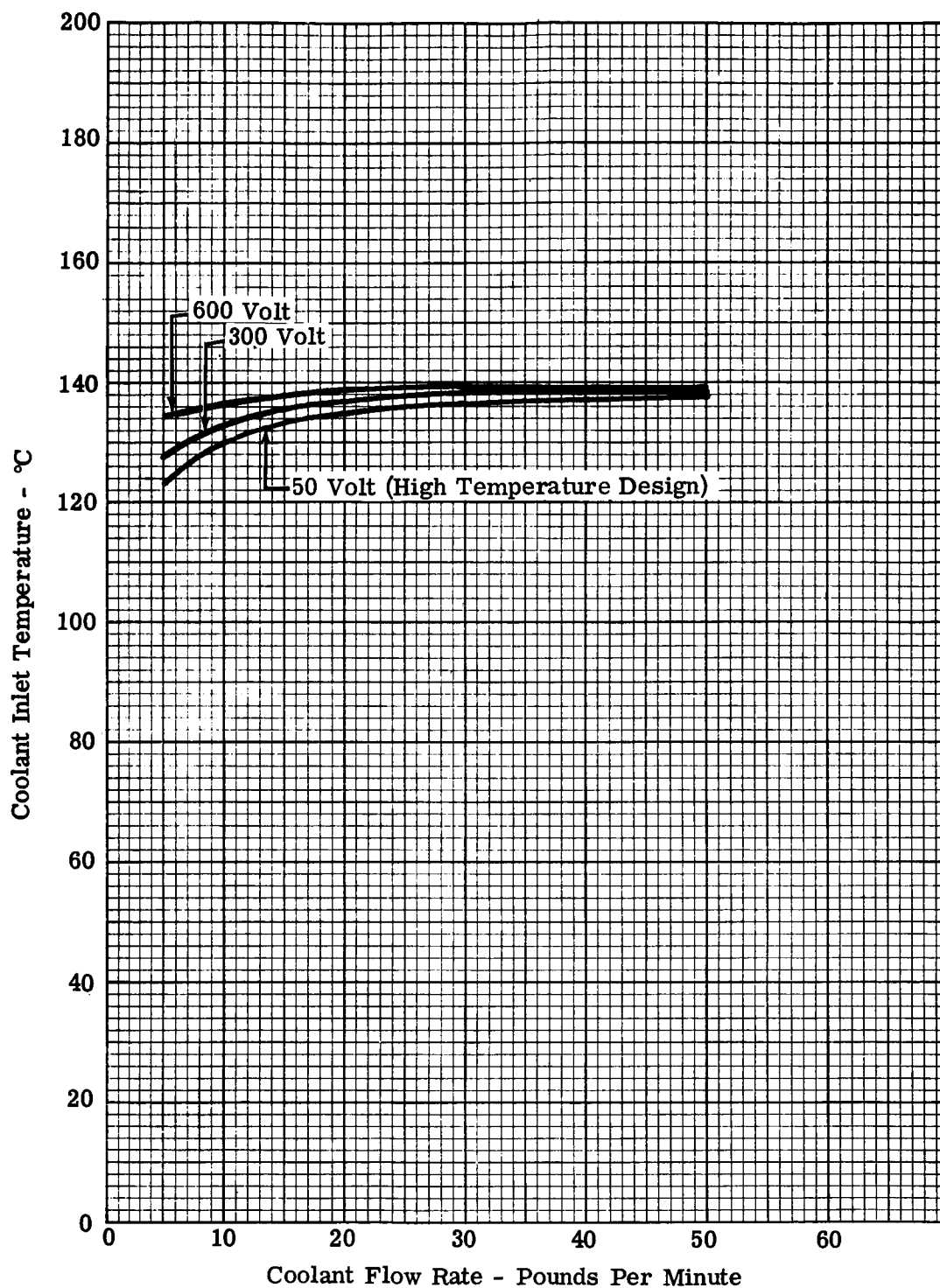


FIGURE 9
Input Filter
One Megawatt, 1000 Cycle Per Second Frequency
Coolant Inlet Temperature Vs. Coolant Flow Rate

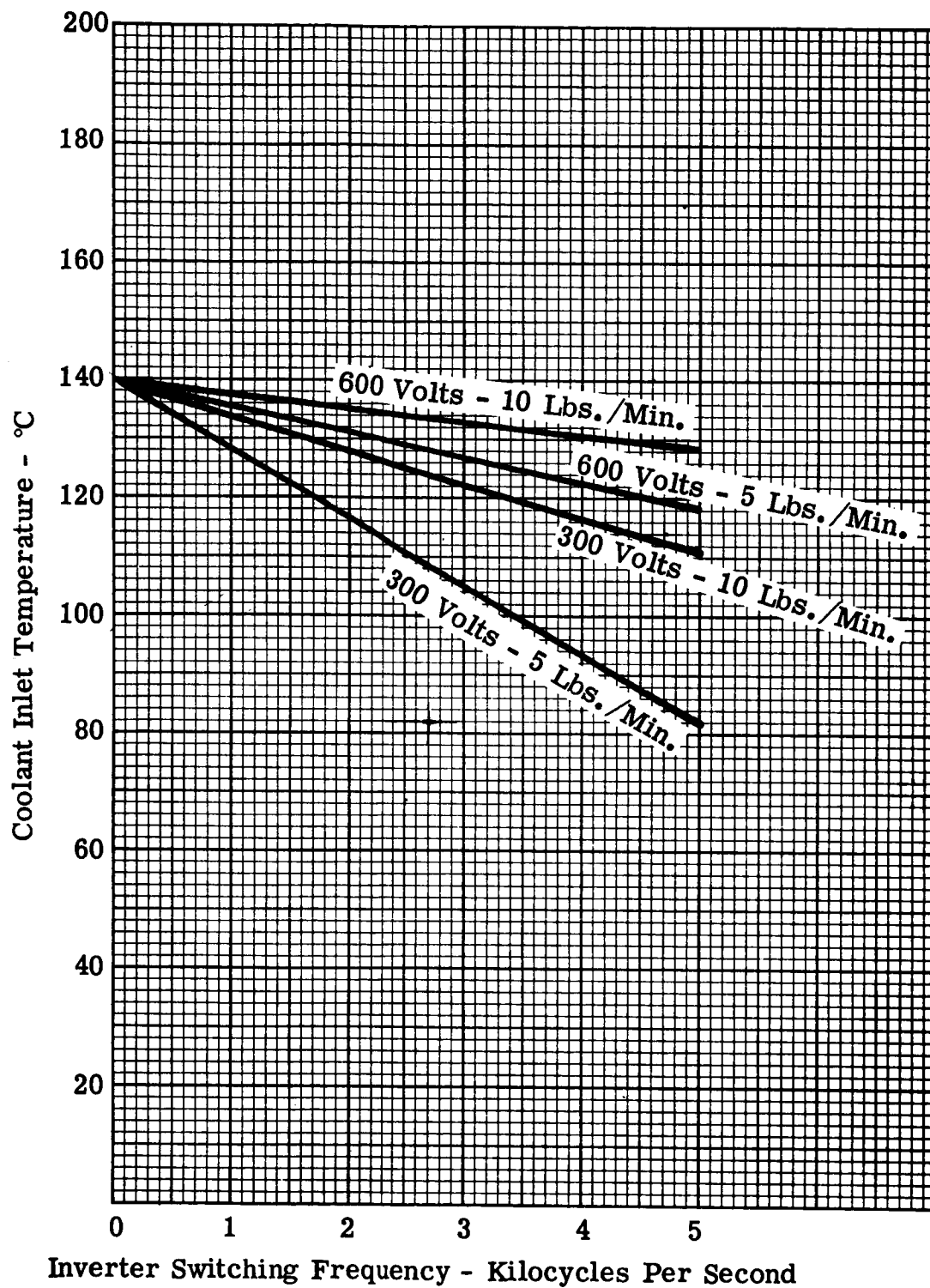


FIGURE 10
Input Filter
Coolant Inlet Temperature Vs. Inverter Switching Frequency

A coolant flow rate of 5 to 10 pounds per minute is recommended for an inverter switching frequency of 1000 cycles per second.

From Table 3, losses are directly proportional to frequency. As a result, for constant flow rate, the required coolant inlet temperature drops with increasing frequency, and for constant temperature, the required flow rate rises substantially. Thus, the use of lower frequencies provides the advantage of easier cooling.

Input filters for the high temperature design are larger and heavier than those for low temperature designs, and also yield higher losses than the equivalent one megawatt load temperature designs. Thus, the use of low temperature designs appears desirable, and from previous discussion, the 600 volt, one and two megawatt designs are the most attractive.

The use of beryllium is recommended for coolant tubes and structure to achieve a lower weight system. A program should be implemented to develop reliable forming and joining techniques for beryllium.

B. INVERTER SWITCHING CIRCUITS

To obtain satisfactory performance the inverter must be designed to fit a particular set of input and output conditions. Because there are 16 combinations of input voltage and output power specified in the contract, plus one high temperature system, a total of 17 different inverters are evaluated.

All of the inverters have the following features in common:

1. A complete inverter is made up of several individual modules, or stages, whose outputs add together to produce the total output.
2. Each inverter has two types of modules; regulated and unregulated.
3. Regulation of output voltage is achieved by turning off the proper number of regulated modules.
4. All modules in all inverters use a single-phase center tapped circuit arrangement. Different types and ratings of components are used for the different voltage and power levels. The single-phase center tapped circuit was chosen for the reasons explained in the "Preliminary Design" section of this report.

The summary of the various inverter designs, showing the type of switching element and the number of modules used, is presented in Table 5.

The three types of module circuits are shown in Figure 11. The transformers shown in the figure are not part of this functional block and are considered separately. The switching elements used for this study are not available today. The characteristics shown in Tables 6 through 9 represent the best estimates of what will be available in five years.

Electrical Design

Operation

Single Value Output System - The following apply to any of the circuits of Figure 11. The secondaries of all the module transformers are effectively in series, so that current is the same in all modules. The switching elements (transistors, controlled rectifiers, or thyratrons) in each module receive alternating drive signals from a separate source called the drive amplifier. In response to the drive signals the two switching elements turn on and off alternately, thus applying d-c power alternately to the two halves of the transformer primary. This action induces a square wave voltage in the transformer secondary. Since all the modules operate in synchronism, the result is a single-phase square-wave output from the inverter.

TABLE 5

LIST OF INVERTER DESIGNS

20 Volt Systems:

Switching Element: Silicon Transistor

Power Output	500KW	1MW	2MW	5MW
Voltage Output	5KV	5KV	20KV	600-5000 V
No. Inv. Stages	550	1100	2200	5500
No. Fixed	412	824	1648	3890
No. Regulated	138	276	552	1610

100 Volt Systems:

Switching Element: Silicon Transistor

Power Output	500KW	1MW	2MW	5MW
Voltage Output	5KV	5KV	20KV	600-5000 V
No. Inv. Stages	110	220	440	1100
No. Fixed	80	160	326	778
No. Regulated	30	60	114	322

300 Volt Systems:

Switching Element: Silicon Controlled Rectifier

Power Output	500KW	1MW	20MW	5MW
Voltage Output	5KV	5KV	20KV	600-5000 V
No. Inv. Modules	24	24	48	192
No. Fixed	18	18	36	136
No. Regulated	6	6	12	56

600 Volt Systems:

Switching Element: Silicon Controlled Rectifier

Power Output	500KW	1MW	2MW	5MW
Voltage Output	5KV	5KV	20KV	600-5000 V
No. Inv. Modules	24	24	48	192
No. Fixed	18	18	36	136
No. Regulated	6	6	12	56

50 Volt High Temperature System:

Switching Element: Vapor Tube Thyratron

Power Output	1MW
Voltage Output	5000 volts d-c
No. Inv. Modules	76
No. Fixed	57
No. Regulated	19

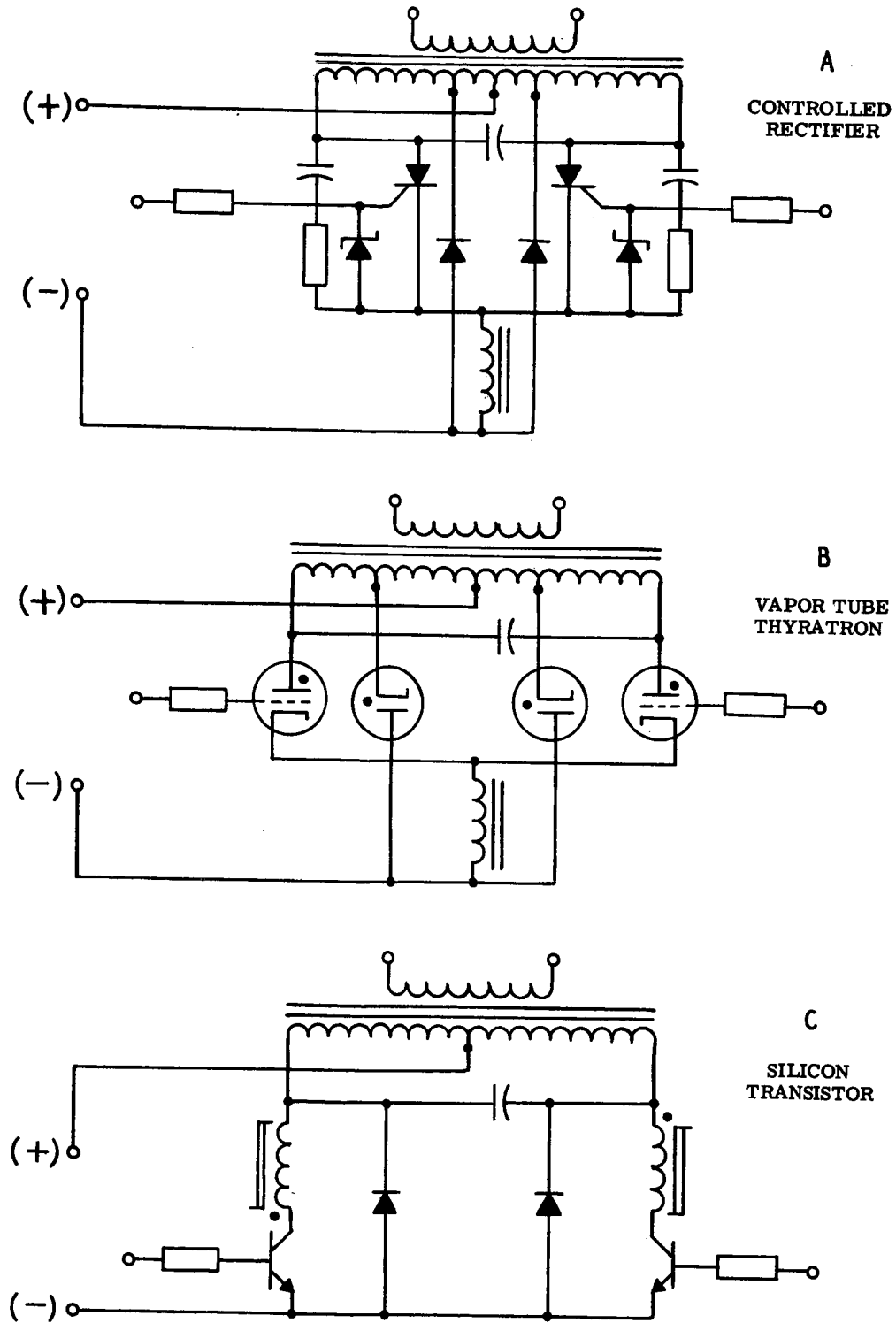


FIGURE 11
Inverter Module Circuits

TABLE 6
CHARACTERISTICS OF SILICON
POWER TRANSISTORS

	<u>1968 (predicted)</u>	<u>1963</u>
Rated Maximum Junction Temperature	200°C	200°C
Rated Collector Current - Amperes	100	70
Rated Collector-Emitter Voltage	400 volts	150 volts
Minimum Gain at 100 Amperes	10	10 at 50 amperes
Minimum Gain at 50 Amperes	15	15 at 35 amperes
V_{be} at $I_C = 50$ Amperes	1.5V Typical 2.5V Maximum	2 volts 3 volts
Saturation Resistance at $I_C = 50$ Amp.	.015 ohm, Typical .02 ohm, Maximum	.035 ohm .045 ohm
Thermal Resistance - Junction to Stud	0.4°C/Watt	0.5°C/Watt
Typical Rise Time at $I_C = 50$ Amperes	2 microsec.	3 microsec.
Typical Fall Time at $I_C = 50$ Amperes	4 microsec.	6 microsec.
Weight	5 oz.	1 oz.
Mechanical Package	Similar to 2N1909 Trinistor Controlled Rectifier	T0-36

TABLE 7
CHARACTERISTICS OF SILICON
CONTROLLED RECTIFIERS

	<u>1968 (predicted)</u>	<u>1963</u>
Rated Max. Junction Temperature	150°C	125°C
Rated Current - Amperes RMS	1000	300
Rated Voltage - Volts	3000	700
Thermal Resistance - Junction to Mounting Surface	0.04°C/watt	0.2°C/watt
Max. Forward Drop - Same as Westinghouse Type 200H, except 6 times current		
Gate Voltage, Max. at $T_j = 90^\circ\text{C}$	3 volts	3 volts
Gate Current, Max. at $T_j = 90^\circ\text{C}$	600 ma	150 ma
<u>Max. Switching Times, Microseconds</u>		
<u>Current - Amperes</u>		
40	20	25
80	24	30
160	30	37
<u>Mechanical Package</u>		
Envelope	3" x 3" base 4" Height	1 5/8" Hex 4 1/4" Height
Terminals	Flat Type	Flexible Lead
Weight	3 lbs.	1.25 lbs.
Mounting	flat surface no stud	stud mounted

TABLE 8
CHARACTERISTICS OF COMMUTATIONG
CAPACITORS

	<u>1968(predicted)</u>	<u>1963</u>
Dielectric Material	Aromatic Polyimide Dupont (ML)	Polycarbonate
Conductor	Foil	Metallized
Density of Winding	.05 lb/cu.in.	.06 lb/cu.in.
Rated Max. Temperature	250°C	120°C
Dissipation Factor	0.1% at 1 kilocycle	0.1% at 1 kilocycle
Capacitance	0.01 to 1 MFD	0.01 to 1 MFD
Bulk Factor of Uncased Capacitor:		
<u>Mfd. x Volts/Cu. In.</u>	<u>Operating Voltage</u>	Same as 1968
70	100	
118	200	
152	400	
182	600	
190	800	
195	1000	
198	1200	
200	1400 and up	

TABLE 9
CHARACTERISTICS OF VAPOR
TUBE THYRATRONS

	<u>1968 (predicted)</u>	<u>1963</u>
Rated Voltage	200 volts	Development
Rated Current	250 amperes	Required -
Forward Voltage Drop	4 volts	Not yet
Rated Envelope Temperature	600°C	Available
Ionization Time	10 microsec.	
Deionization Time	50 microsec.	
Heater Power at 600°C	25 watts	
Size	3 in. Dia. x 6 in. Ht.	
Weight	1.0 lb.	

The voltage and the frequency of the inverter output are proportional to the d-c voltage supplied by the nuclear thermionic power source. At light load the source voltage will rise, tending to raise the output voltage of the inverter. To counteract this tendency, drive signals are removed from some of the inverter modules, causing them to turn off and subtract increments of voltage from the output. The proper number of modules to be turned off is determined by the voltage regulator which is a separate functional block discussed later.

The modules which can be turned off are called regulated modules. They differ from the unregulated modules in two ways. The transformers are larger to enable them to withstand two successive half-cycles of voltage in the same direction. Furthermore, the commutation diodes are larger to enable feedback of transformer primary current while the modules are in the off mode of operation.

Hence, the regulated modules are somewhat heavier than the unregulated modules and it is desirable to minimize their number. Calculations have shown that the minimum number of modules required to maintain ± 5 percent voltage regulation is 24, of which 6 modules are the regulated type. Some of the single value output systems use this minimum number while other systems need more modules to achieve the required power outputs.

Dual Output Voltage - An inverter for any one of these systems consists of a group of 8 inverters of the type described above. Each inverter is connected to its own separate transformer and rectifier. Low output voltage (600V d-c) is obtained by paralleling the rectifiers while high voltage (5000V d-c) is obtained by connecting the 8 rectifiers in series.

These two connections produce a voltage variation of 8 to 1 or 5000 to 625 volts. The additional 25 volts is eliminated by turning off one or more modules in each group during low voltage operation. Because each separate inverter must be capable of voltage regulation to ± 5 percent, each inverter requires a minimum of 24 modules, giving a total of 192 modules in the system. Of this number, 56 modules are the regulated type.

In the special case of the 600 volt input, 600-5000 volt output system, a converter is not strictly necessary for the 600 volt output. The power could be taken directly from the reactor bus. However, a regulator would be required to maintain correct voltage and this would be a large piece of equipment. Since a converter is required for the 5000 volt output, it seems reasonable to use it to generate the low voltage as well, thus saving the extra weight of a separate regulator.

High Temperature System - A one-megawatt inverter using high temperature tubes was studied to show a comparison with semiconductor inverters. When making this comparison, it must be remembered the tubes will probably have a shielding weight advantage that was not considered in this study.

Design Criteria

The intention is to predict the characteristics of inverters that might be built five years in the future. Hence the major components used in this study are types not available today. The power switches, diodes, and capacitors are advanced units whose characteristics have been estimated.

The predicted characteristics of the components to be available in 1968 have been resolved through consultations with component suppliers and NASA. The predicted characteristics are based on normal industry progress and are intended to be realistic estimates of what will be available in 1968.

The predicted characteristics of the power transistors, silicon controlled rectifiers, vapor tube thyratrons and capacitors used in this study are shown in Tables 6 through 9. Presently available components are also used, where suitable.

To help assure long component life all components are operated at less than the maximum ratings. Operating levels of voltage and current are generally one-half the rated values for the components, and operating temperatures are held to 75% or less of the rated maximum temperatures. For example, silicon diodes, rated 100 amperes, 400 volts at 200°C junction temperature are operated at no more than 50 amperes, 200 volts, 150°C maximum temperature. In many cases, high switching losses have required that components be operated at even less than half rated voltage and current.

All the inverters have been evaluated over the switching frequency range of 50 cps to 5000 cps. The lower switching frequencies have the advantage of reducing losses in the switching elements, while high frequencies result in less transformer weight. It is believed that the range of 50 to 5000 cps is broad enough to encompass all practical designs, and that the optimum converter frequency will lie within this range when a system analysis is made. Determination of the optimum frequency is outside the scope of the present study.

Other considerations used to prepare the parametric data for the inverter switching circuits are presented in the following assumptions.

1. The power conversion equipment must maintain rated output voltage at $\pm 5\%$ over the range from no load to full load.

2. The systems must withstand open or short circuit faults at the high voltage bus without damage. The full load operating point of the nuclear-thermionic source is such that maximum open circuit voltage will not exceed two times the full load value. The maximum short circuit current will not exceed 3 per unit load current.
3. The power conditioning system is required to operate continuously at no more than 1.25 per unit load current.
4. The selection of the inverter circuits to be studied was determined on the basis of minimum weight.

Parametric Data

The electrical parametric data, generated during the study of inverter functional blocks, is shown in the following tables. Table 10 summarizes the calculated inverter heat loads, showing how the heat rejected increases with operating frequency.

The major power loss in the inverters occurs in the switching elements in the form of forward voltage drop and switching losses. At low frequencies the forward drop is predominant, but as frequency increases, the switching loss becomes more important. These facts are illustrated in Figure 12, which shows the calculated losses in each of the three types of switching devices under typical conditions encountered in the study. The transistor losses are lowest because the transistor can switch off in less time than the other two devices. The vapor tube thyatron has the highest losses because of its high voltage drop and slow switching speed.

Calculated efficiencies of the various inverter designs are summarized in Table 11. The figures represent inverters only, and do not take into account losses in transformers or drive circuits. These other functional blocks are discussed later. The curves of Figures 13, 14, and 15 show typical variations of inverter heat loads and efficiencies with respect to power rating, switching frequency, and input voltage.

Problem Areas

The high temperature converters pose two major problem areas. It was assumed that the high temperature vapor tubes would have characteristics somewhat similar to low temperature gas tube thyatrons; specifically that they could be turned on by grid control, but could only be turned off by interrupting the anode current. Thus, they would require a capacitor to store energy for turn-off. One problem is that capacitors capable of withstanding the 600°C envelope temperatures proposed for the tubes are not available. The highest temperature capacitors presently available are usable to about 300°C and weigh about five times as much as units designed for lower temperatures. Sufficient improvement is not expected in these properties within five years if normal trends are followed.

TABLE 10

SUMMARY OF INVERTER HEAT LOADS

System Rating Input Volts Output Kilowatts		Switching Element	Inverter Heat Loads at Prescribed Switching Frequencies						
			50	100	200	500	1000	2000	5000 ← cps
20	500	Silicon Transistor	33.3	33.5	33.9	35.2	36.6	39.8	50.3 ← kw
20	1000	Silicon Transistor	66.6	67	67.8	70.4	73.2	79.6	100.6 kw
20	2000	Silicon Transistor	133.2	134	135.6	140.8	146.4	159.2	201.2 kw
20	5000	Silicon Transistor	333	335	339	352	366	398	503 kw
50	1000	Vapor Tube Thyratron	128	132	138	157	190	254	446 kw
100	500	Silicon Transistor	7.20	7.42	7.75	8.96	10.61	14.3	25.3 kw
100	1000	Silicon Transistor	14.40	14.84	15.50	17.92	21.22	28.6	50.6 kw
100	2000	Silicon Transistor	28.8	29.7	31.0	35.8	42.4	57.2	101.2 kw
100	5000	Silicon Transistor	72.0	74.2	77.5	89.6	106	143	253 kw
300	500	Silicon Cont. Rectifier	5.34	5.38	5.71	6.8	8.56	12.04	22.63 kw
300	1000	Silicon Cont. Rectifier	8.23	8.69	9.45	11.7	15.5	23.5	45.4 kw
300	2000	Silicon Cont. Rectifier	16.46	17.38	18.9	23.4	31.0	47.0	90.8 kw
300	5000	Silicon Cont. Rectifier	43.8	46.3	49.1	59.9	81.4	112.5	222 kw
600	500	Silicon Cont. Rectifier	3.58	3.65	3.99	4.93	6.55	9.62	18.0 kw
600	1000	Silicon Cont. Rectifier	5.66	5.93	6.70	8.69	12.0	18.5	38.2 kw
600	2000	Silicon Cont. Rectifier	11.3	11.9	13.4	17.4	24.0	36.9	76.5 kw
600	5000	Silicon Cont. Rectifier	37.1	38.6	42.5	51.3	66.1	99.5	193 kw

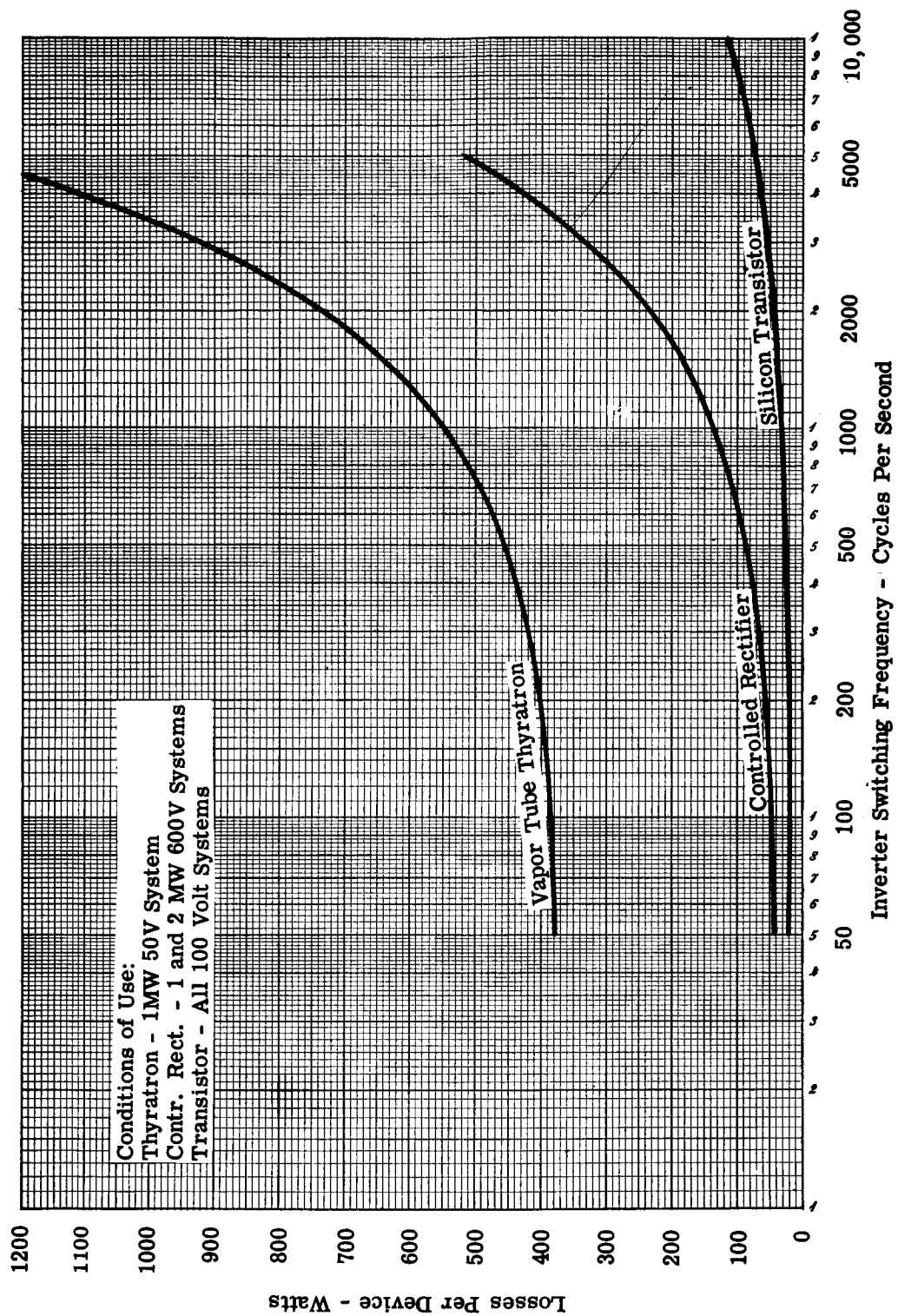


FIGURE 12
 Inverter Switching Element
 Power Losses Vs. Frequency

TABLE 11

SUMMARY OF INVERTER EFFICIENCIES

System Rating Input Volts Output Kilowatts		Switching Elements	Inverter Efficiencies at Prescribed Frequencies						
			50	100	200	500	1000	2000	5000 ←cps
20	500	Silicon Transistors	93.9	93.9	93.8	93.5	93.2	92.7	91.0 ←---
20	1000	Silicon Transistor	93.9	93.9	93.8	93.5	93.2	92.7	91.0 %
20	5000	Silicon Transistor	93.9	93.9	93.8	93.5	93.2	92.7	91.0 %
50	1000	Vapor Tube Thyratron	88.6	88.4	88.0	86.5	84.1	79.7	69.2 %
100	500	Silicon Transistor	98.6	98.5	98.4	98.3	98.0	97.4	95.2 %
100	1000	Silicon Transistor	98.6	98.5	98.4	98.3	98.0	97.4	95.2 %
100	2000	Silicon Transistor	98.6	98.5	98.4	98.3	98.0	97.4	95.2 %
100	5000	Silicon Transistor	98.6	98.5	98.4	98.3	98.0	97.4	95.2 %
300	500	Silicon Cont Rectifier	98.9	98.9	98.9	98.6	98.3	97.6	95.0 %
300	1000	Silicon Cont Rectifier	99.2	99.1	99.0	98.8	98.4	97.6	95.5 %
300	2000	Silicon Cont Rectifier	99.2	99.1	99.0	98.8	98.4	97.6	95.5 %
300	5000	Silicon Cont Rectifier	99.1	99.1	99.0	98.8	98.4	97.6	95.6 %
600	500	Silicon Cont Rectifier	99.3	99.3	99.2	99.0	98.7	98.1	96.3 %
600	1000	Silicon Cont Rectifier	99.4	99.4	99.3	99.1	98.8	98.1	96.1 %
600	2000	Silicon Cont Rectifier	99.4	99.4	99.3	99.1	98.8	98.1	96.1 %
600	5000	Silicon Cont Rectifier	99.3	99.2	99.1	99.0	98.7	98.0	96.1 %

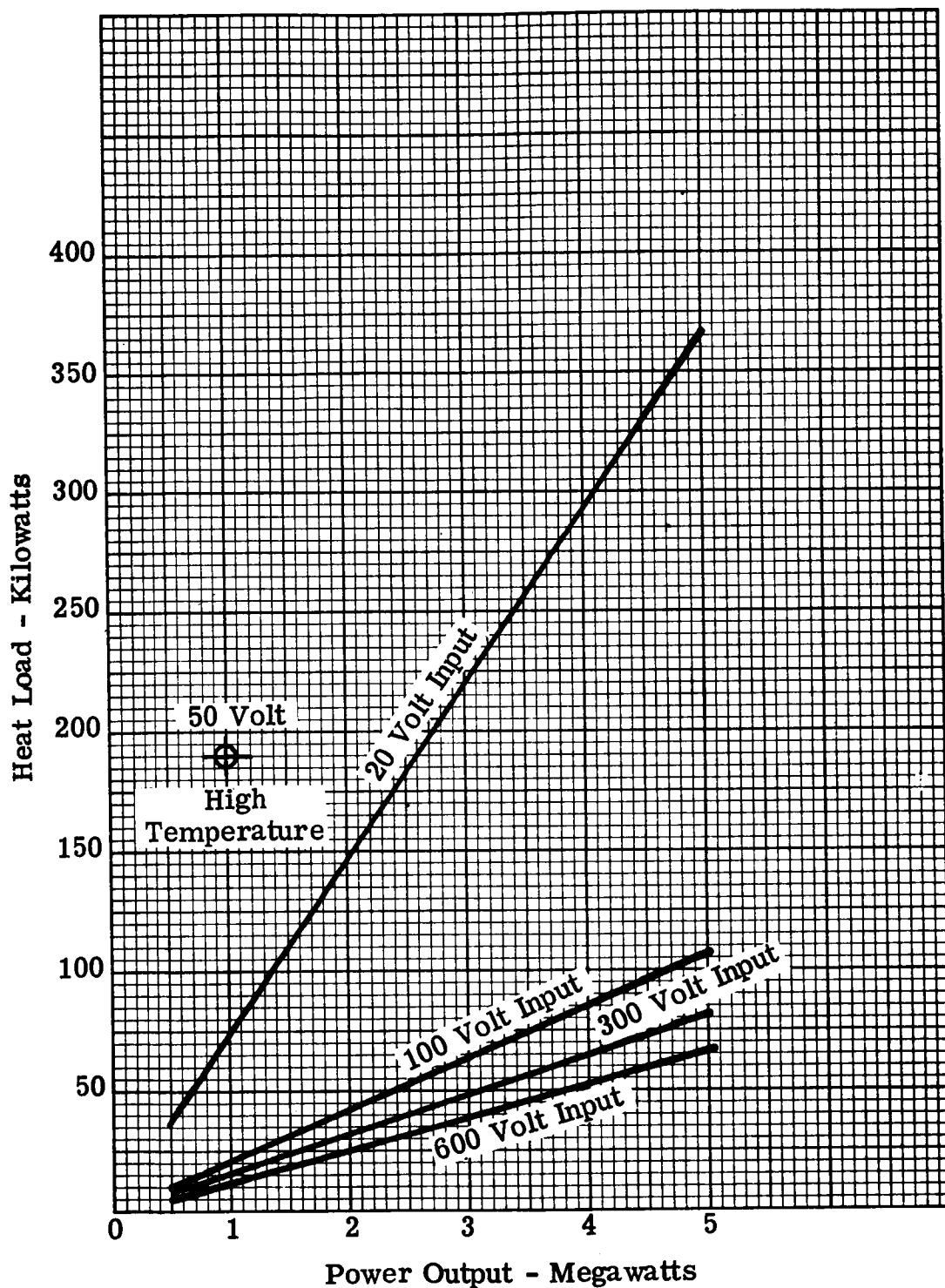


FIGURE 13

Inverter
1000 Cycles Per Second
Heat Loads Vs. Power Output

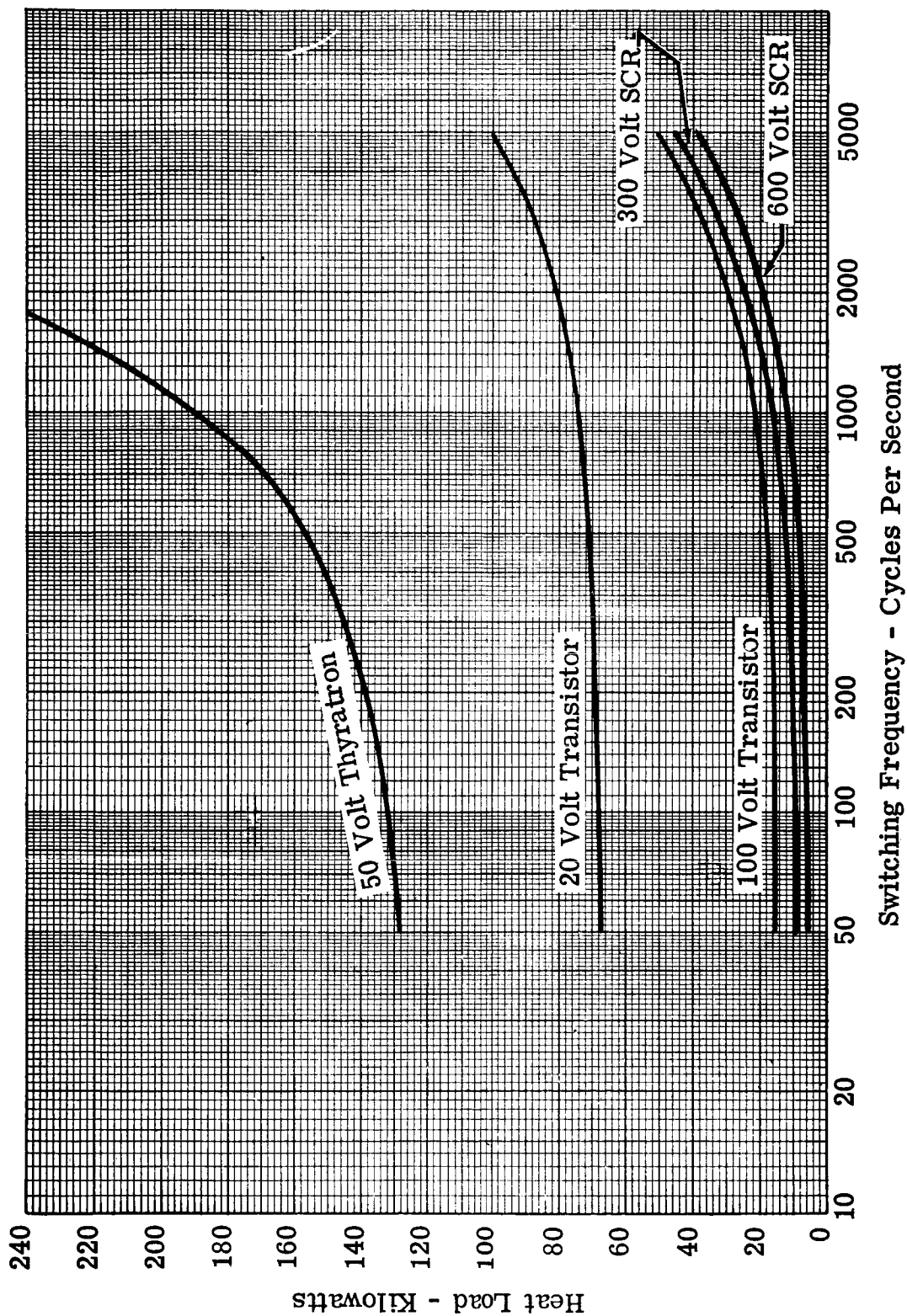
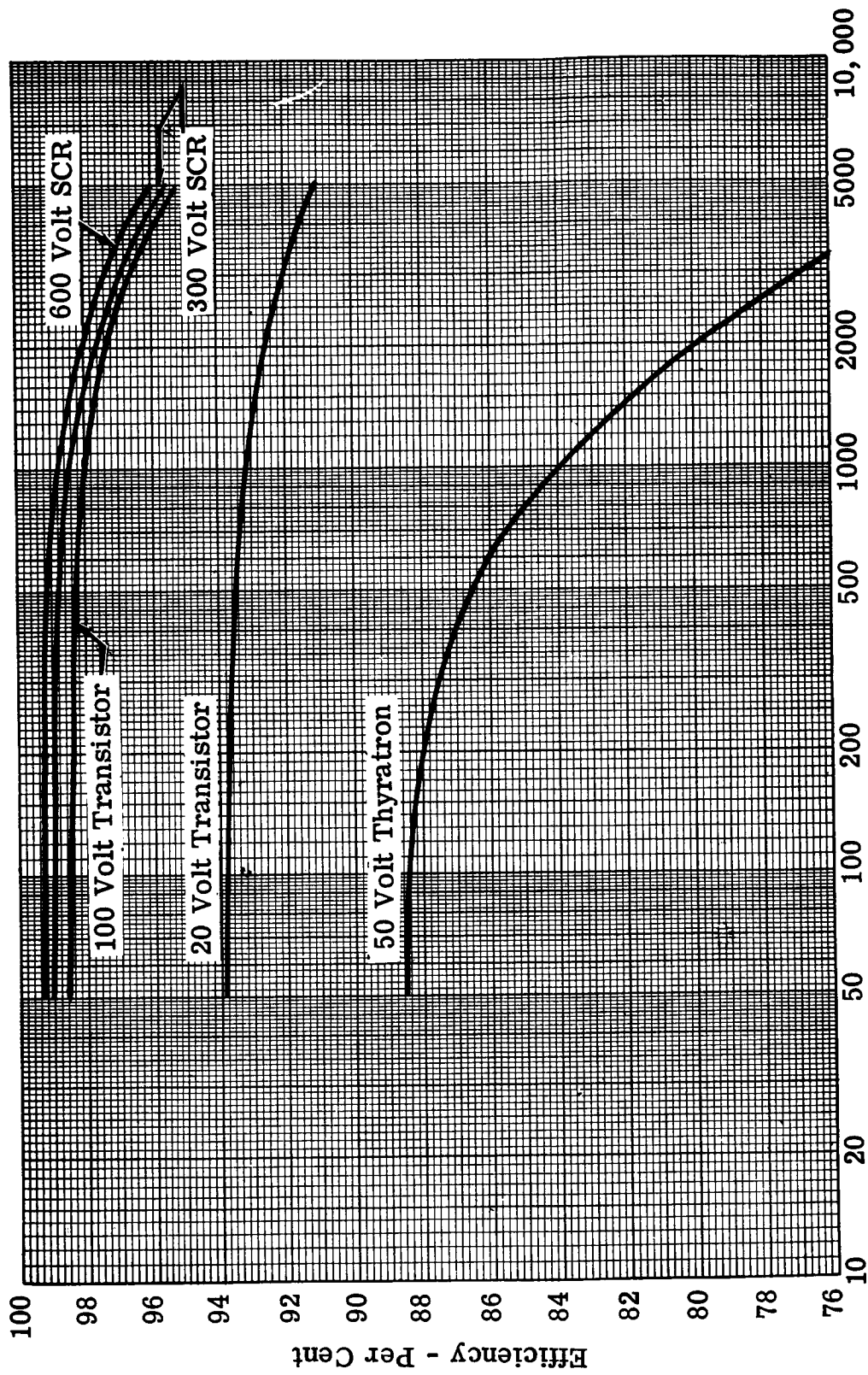


FIGURE 14

Inverter
One Megawatt
Heat Loads Vs. Switching Frequency



Switching Frequency - Cycles Per Second

FIGURE 15

Inverter
1 Megawatt
Efficiency Vs. Switching Frequency

The problem was circumvented for purposes of this study by using low temperature (250°C) capacitors and providing a cooling system that is thermally isolated from the high temperature cooling system. However, a high temperature capacitor would result in a lighter, simpler system.

A second problem that arises in connection with high temperature vapor tubes is that of supplying power to the filaments. A-C power is not available so the customary filament transformers cannot be used. It is necessary to provide a source of regulated d-c, probably at a low voltage. This requires a device capable of regulating low d-c voltages at high current levels and operating at high temperature. Such a device is not available at this time, although possibly something analogous to a gas VR tube could be developed to suit this application.

Analysis and Recommendations

Several interesting points are brought out by the data summarized in Tables 10 and 11. The first is that inverter efficiency does not rise appreciably as power rating increases. That is, a 500kw inverter of a given input voltage and frequency has substantially the same efficiency as a 5000kw unit. The explanation for this is that the basic inverter module is much smaller than 500kw, and to develop the levels of power required in this study, large numbers of the basic modules are used. Thus, the efficiency of the complete inverter is the same as the efficiency of one module. While the modules used for different power ratings are not identical, considerations of cooling and semiconductors dictate that modules be enough alike to yield similar efficiencies.

The second point of interest is that there is a gain in efficiency as the nominal input voltage is raised. This effect is most pronounced when going from 20 volts to 100 volts, with a much smaller gain above the 100 volt level. The explanation is simply that the forward conduction voltage drop of the switching elements becomes a smaller fraction of the supply voltage, as the supply voltage is raised. Note that this is also a reason for the very low efficiency calculated for the special case of vapor tube switching elements.

Third, it is noticed that the efficiency goes down as the frequency goes up. This is a natural consequence of the increase of switching loss with frequency displayed by all static switching elements.

Transistors were chosen to be the switching elements for inverters operating at 100 volts and lower because a preliminary analysis indicated that this would result in the lightest weight propulsion system.

However, the transistor inverters have one major disadvantage that will probably prevent their use in an actual system of the size considered in this study. That is the extremely large number

of parts required to make up the inverter. For example, the inverter for the 5000 kilowatt, 20 volt system requires 5500 modules, each one containing two transistors. Thus, there are 11,000 transistors in the inverter alone. Such a large number of parts would require an excessively long manufacturing time, both for the components and for the inverter assembly. In addition, reliability of the resulting system would almost certainly be inadequate.

Secondary to the above considerations for purposes of this study, but very important in an actual system, is cost. A rough estimate places the cost of each transistor at 400 dollars. Multiplied by 11,000 transistors, this results in a total cost of 4.4 million dollars for transistors alone. Based on these considerations, it is recommended that the 20 volt, 5 megawatt; 20 volt, 2 megawatt, and 100 volt, 5 megawatt systems be excluded from further study.

Referring to Tables 10 and 11, it is seen that the high temperature inverter using vapor tubes is the least efficient of all the inverters studied. This results primarily from the fact that the vapor tube thyratrons have a relatively high voltage drop during conduction compared to their reverse voltage rating.

Because of this situation, and the other problems previously mentioned under "Problem Areas", the following recommendations are made with regard to high temperature systems.

1. High-temperature vapor-tube thyratrons should be developed for higher voltage ratings than presently proposed. The ratings should extend to at least 600 volts, and preferably 1000 volts with no increase in forward voltage drop. This permits the tubes to be used at higher input voltage, thus making the forward conduction loss smaller in comparison to the total power switched by the tube.
2. An attempt should be made to develop high temperature vapor tube thyratrons with deionization times considerably less than the 50 microseconds presently proposed. This permits efficient inverter operation at higher frequencies, thus reducing not only inverter weight, but the weight of power transformers and filters as well.
3. Capacitors are required as filtering and commutating elements in high temperature inverters. It would be desirable to develop capacitors that are capable of operating at a case temperature of 600°C with dissipation factor of less than 1%, and size and weight comparable to ordinary paper capacitors. There has been very little demand for such units in the past, but the demand will increase as more power equipment for space applications is planned.

4. Attention should be given to the problem of providing regulated low voltage d-c power to the filaments of the proposed high temperature tubes, and to making the tubes capable of operating for long periods with d-c filament power.

The inverters that use silicon controlled rectifiers appear to be the best when only factors of this study are considered. However, any statements comparing silicon semiconductors to vapor tube thyratrons in d-c to d-c converter systems which incorporate the thermionic-nuclear reactor and the electrostatic thruster load must be reserved until a systems study is completed. Factors which must be considered in the systems study are shielding weights for the semiconductor equipment and the possible greater cable lengths which may be required in locating the semiconductor equipment a specified distance from the space vehicle nuclear reactor.

The following recommendations are intended to enhance the advantages of controlled rectifiers for this specific application.

1. Develop silicon controlled rectifiers capable of operating for extended periods at higher temperatures than presently available devices. A rating of 200°C would be desirable, even if it resulted in poor operation at temperatures below 0°C.
2. Develop silicon controlled rectifiers with faster turn-off times at high temperature than present units. Turn-off times of the order of 5 to 10 microseconds at 100 amps and 150°C junction temperatures would be a worthwhile improvement.
3. It is desirable to determine the effects of nuclear radiation on silicon controlled rectifiers and attempt to manufacture devices that are more radiation resistant than present devices.

MECHANICAL DESIGN

Description

The silicon transistor and controlled rectifier inverter mechanical design is based on the cold-plate cooling with eutectic NaK coolant. Semiconductors are adhesive bonded to insulation, which in turn is adhesive bonded to the cold plate. Adhesive bonding is used to reduce the thermal resistance across the joints in a space environment. Mechanical fastening is used in conjunction with bonding to insure reliable construction.

Beryllium oxide insulation is used to provide dielectric strength and to provide a good thermal path from components to the cold plate. The insulation thickness under the transistors and commutating diodes is dictated by thermal conduction requirements.

Sufficient cross-sectional area of insulation is required to transfer heat laterally from the semiconductors to the coolant tubes with low temperature drop. Elsewhere, insulation thickness of .040 inch is assumed over the cold plate. The insulation sheet is assumed to be segmented into four to five inch sections to provide relief from thermal stress in adhesive bonding. The choice of thickness is based on assumed mechanical strength and handling requirements. For dielectric purposes this thickness is sufficient to withstand voltages up to three kilovolts, which is higher than the voltages actually present.

Coolant tubes and cold plate are of beryllium to achieve low weight with the required resistance to corrosion by liquid metal. Components are arranged in modules and mounted in rows to the cold plate. In the 20 and 100 volt designs each row is cooled by two coolant ducts parallel to the row. In the 300- and 600-volt systems each row is cooled by four ducts.

For comparative purposes two high temperature designs were studied for a one megawatt power rating utilizing vapor tube thyratrons and vapor tube commutating diodes. Electrical connections from the vapor tube devices are assumed to serve as mounting flanges and to provide heat conduction paths. The flanges are mounted through beryllium oxide insulation to a cold plate which has integral coolant ducts routed adjacent to the vapor tubes. The devices are cooled directly by conduction from the flanges to the cold plate through the beryllium oxide insulation. The electric conducting flanges are adhesive bonded to the insulation to reduce thermal resistance across the joint and are mechanically fastened to ensure structural reliability. The insulation is adhesive bonded to the cold plate. Cold plate and cooling tubes are of titanium in the high temperature circuit and beryllium in the low temperature circuit.

Commutating capacitors, grid resistors, and commutating inductors in one high temperature design are mounted to a cold plate designed to maintain a capacitor maximum internal temperature of 250°C, and shielded from the vapor tubes. In a second version the commutating inductors are included in the high temperature coolant circuit. The vapor tube cooling is designed to maintain the temperature at the mounting surface of the electrical flange connections to 600°C maximum.

Design Criteria

The following design criteria are used to calculate the required parametric data.

1. The coolant is assumed to be eutectic NaK, which has a specific heat of 0.210 Btu/lbs.-°F, and a density of 0.0306 lbs./in.³. Convection temperature drop is assumed to be 1°C.
2. Beryllium oxide insulation has the following characteristics:

Dielectric Strength	300 volts/mil
Density	0.105 lbs./in. ³
Thermal Conductivity	100 Btu/hr-ft-°F at 100°C
Thermal Expansion	3.2 x 10 ⁻⁶ in/in/°F from 0 to 200°C
	5.0 x 10 ⁻⁶ in/in/°F from 400 to 600°C
3. Beryllium for use in coolant tubes and cold plate has the following characteristics:

Density	0.067 lbs./in. ³
Thermal Conductivity	87 Btu/hr-ft-°F
Thermal Expansion	6.4 x 10 ⁻⁶ in/in/°F
4. Columbium for use in coolant tubes, cold plate, and flanges has the following characteristics:

Density	0.310 lbs./in. ³
Thermal Conductivity	31.5 Btu/hr-ft-°F
Thermal Expansion	3.82 x 10 ⁻⁶ in/in/°F
5. Titanium for use in coolant tubes, cold plate, and flanges has the following characteristics:

Density	0.163 lbs./in. ³
Thermal Conductivity	4.3 Btu/hr-ft-°F
Thermal Expansion	5.8 x 10 ⁻⁶ in/in/°F
6. Adhesive bonding is .002 inch thick, with a thermal conductivity of 0.227 Btu/hr-ft-°F.
7. Minimum achievable thermal resistance between two surfaces not bonded together is 0.2°C/watt in a space environment.
8. Semiconductor junction temperatures are 150°C for transistors and 112°C for silicon controlled rectifiers, equivalent to 25 per cent derating. Case and stud temperature is dictated by the thermal resistance and losses for each particular case.
9. Vapor tube devices have an allowable case temperature of 600°C. For the flange-mounted, conduction-cooled design, the electrical connections, which serve as mount flanges, are assumed to be held to 600°C.

9. Supporting structure weight, not included in the weight of cold plate, insulation, and coolant tube is assumed to be 20 percent of the total weight.

Parametric Data

Total weight and volume and specific weight for all circuits are presented in Table 12, as well as required coolant inlet temperature for silicon semiconductor circuits at a frequency of 1000 cycles per second and a flow rate of 120 pounds per minute. A breakdown of losses between high-temperature and low-temperature components in vapor tube designs is given in Table 13. Parameters for silicon semiconductor inverter circuits are given in Figures 16 through 20.

Additional parameters for high temperature circuits using vapor tube thyratrons are given in Figures 21 through 26.

Figure 16 shows total inverter weight as a function of power rating at an input frequency of 1000 cycles per second for input voltages of 20, 100, 300, and 600 volts. For the 300- and 600-volt circuits dashed lines show an extrapolation of the 0.5-, 1.0-, and 2.0-megawatt designs, indicating the weight penalty inflicted by the dual output voltage, 5-megawatt design. Figure 17 gives package volume as a function of power rating for the four design input voltages at 1000 cycles per second.

Figures 18, 19, and 20 present parameters for the 200- and 600-volt, one-megawatt designs which are typical for all designs. These particular designs were chosen for display of typical parameters because they have the lowest specific weights of the alternatives considered. Figure 18 gives required coolant fluid inlet temperature as a function of coolant flow at 1000 cycles per second. This was determined from Figure 8 at an assumed coolant conduit wall temperature of 102°C. Figure 19 shows variation of coolant fluid inlet temperature with frequency at flow rates of 120 and 240 pounds per minute.

Figures 21 through 24 show variation of coolant fluid inlet temperature with flow rate at frequencies of 1000-, 2000-, and 5000 cycles per second for the high temperature inverter. Figures 21 and 22 are for the design in which commutating inductors are cooled by the low temperature cooling circuit. Figures 23 and 24 are for the design in which inductors are mounted to the high-temperature coolant circuit. Figures 21 and 23 give data for the high-temperature coolant circuit; Figures 22 and 24 give data for the low-temperature circuit. Figures 25 and 26 present effects of frequency on inverter circuit weight and coolant inlet temperature for the high-temperature design.

TABLE 12

INVERTER SWITCHING CIRCUIT
MECHANICAL DESIGN PARAMETERS

Frequency - 1000 CPS

Inverter Rating (megawatts)	500	1	2	5
<u>20 Volt Transistor Systems</u>				
Total Weight (lbs)	2110	4220	8450	21250
Total Volume (cu. ft.)	92.7	185.2	371.0	931.0
Specific Weight (lbs/kw)	4.22	4.22	4.225	4.25
Coolant Inlet Temp., °C (1000 cps, 120 lbs/min)	85	39	*	*
<u>100 Volt Transistor Systems</u>				
Total Weight (lbs)	391	782	1564	3920
Total Volume (cu. ft.)	15.7	31.4	62.8	157.6
Specific Weight (lbs/kw)	0.782	0.782	0.782	0.785
Coolant Inlet Temp., °C	112	98	70	*
<u>300 Volt SCR Systems</u>				
Total Weight (lbs)	425	610	1220	3770
Total Volume (cu. ft.)	11.2	17.5	35.0	97.5
Specific Weight (lbs/kw)	0.85	0.610	0.610	0.754
Coolant Inlet Temp., °C	95	78	58	*
<u>600 Volt SCR Systems</u>				
Total Weight (lbs)	361	483	983	3124
Total Volume (cu. ft.)	97	12.3	24.6	86.6
Specific Weight (lbs/kw)	0.722	0.483	0.491	0.625
Coolant Inlet Temp., °C	99	87	73	23
<u>50 Volt Thyratron System</u>				
Total Weight (lbs)	--	5770	--	--
Total Volume (cu. ft.)	--	123	--	--
Specific Weight (lbs/kw)	--	5.77	--	--

*For these design points, at a coolant flow rate of 120 pounds per minute, the required coolant inlet temperature is below the freezing point of eutectic NaK, and therefore, is not applicable.

TABLE 13
HEAT LOADS FOR HIGH TEMPERATURE INVERTERS

Frequency (cps)	Design 1			Design 2		
	Losses, Low Temperature Components (kilowatts)	Losses, High Temperature Components (kilowatts)	Total Losses (kilowatts)	Losses, Low Temperature Components (kilowatts)	Losses, High Temperature Components (kilowatts)	Total Losses (kilowatts)
1000	3.48	186.5	190	18.27	172	190
2000	6.96	247	254	21.75	232	254
5000	17.4	428.6	446	32.2	414	446

NOTE: Design 1 - Inductors and thyratrons are included in high temperature cooling circuit; all other components are in low temperature cooling circuit.

Design 2 - Thyratrons only are included in high temperature cooling circuit; inductors are included with all other components on the low temperature cooling circuit.

Input Voltage = 50 volts

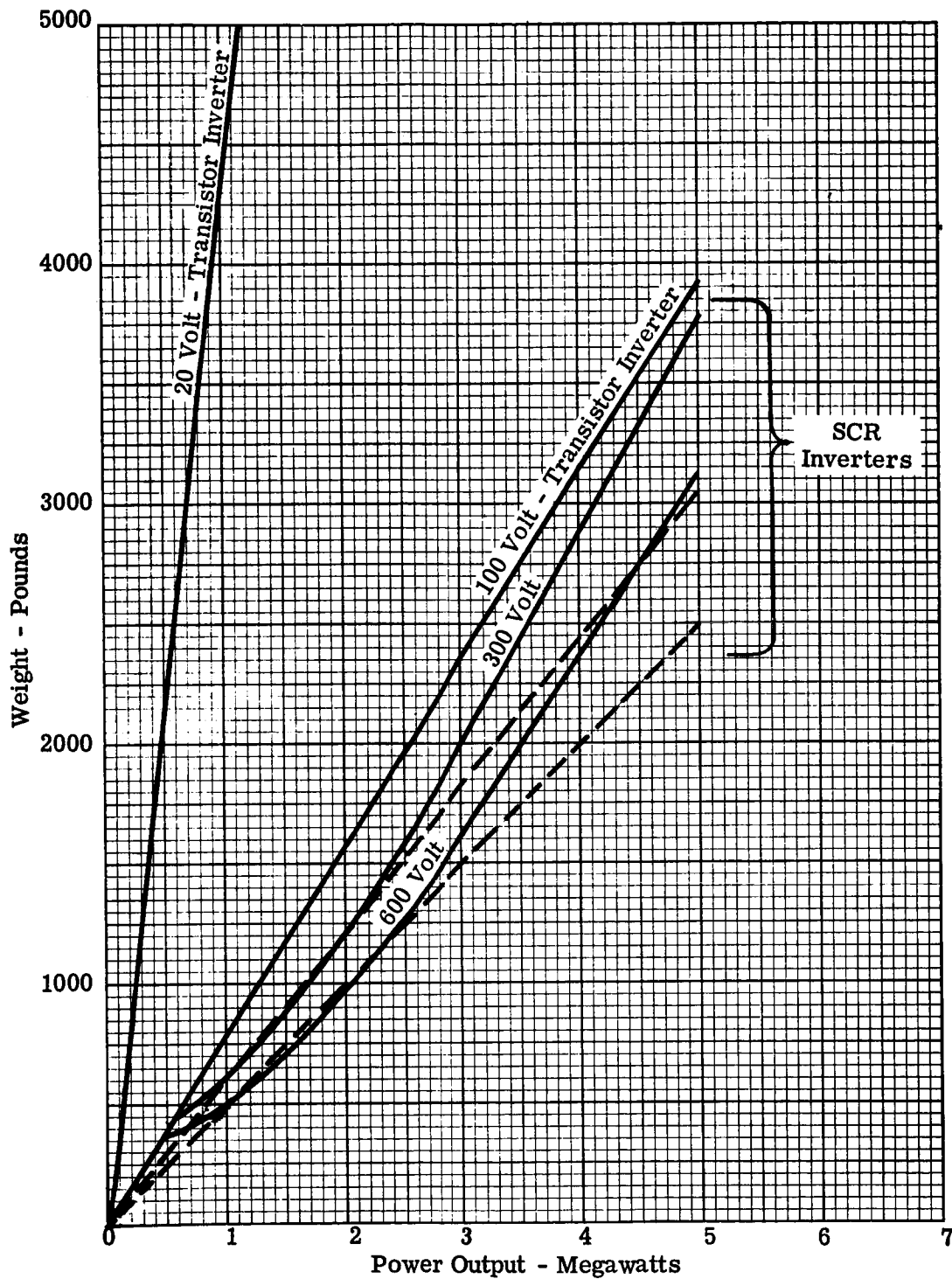


FIGURE 16

Inverter
Silicon Semiconductors, 1000 Cycles Per Second
Weight Vs. Power Output

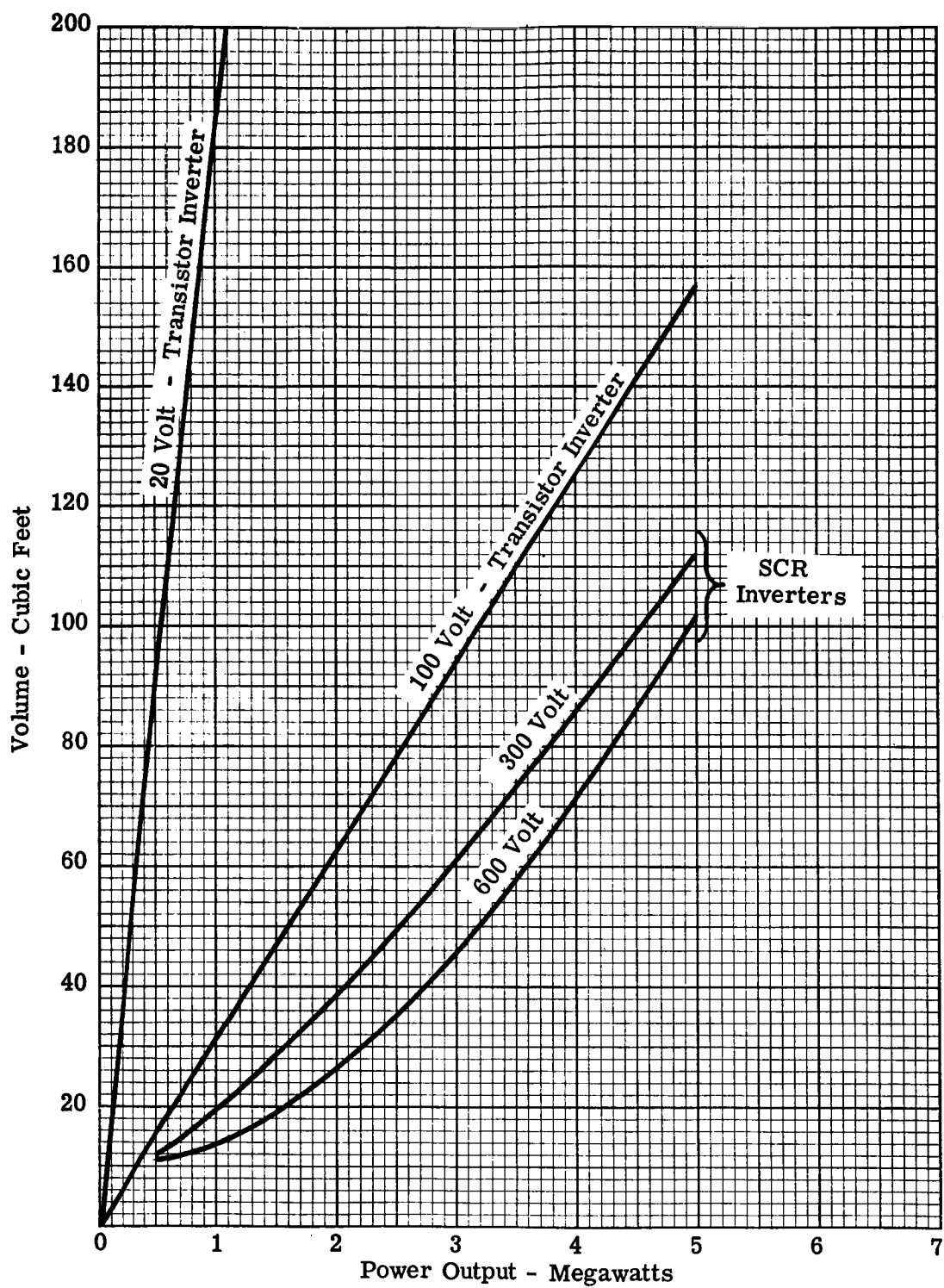


FIGURE 17

Inverter
Silicon Semiconductors, 1000 Cycles Per Second
Volume vs. Power Output

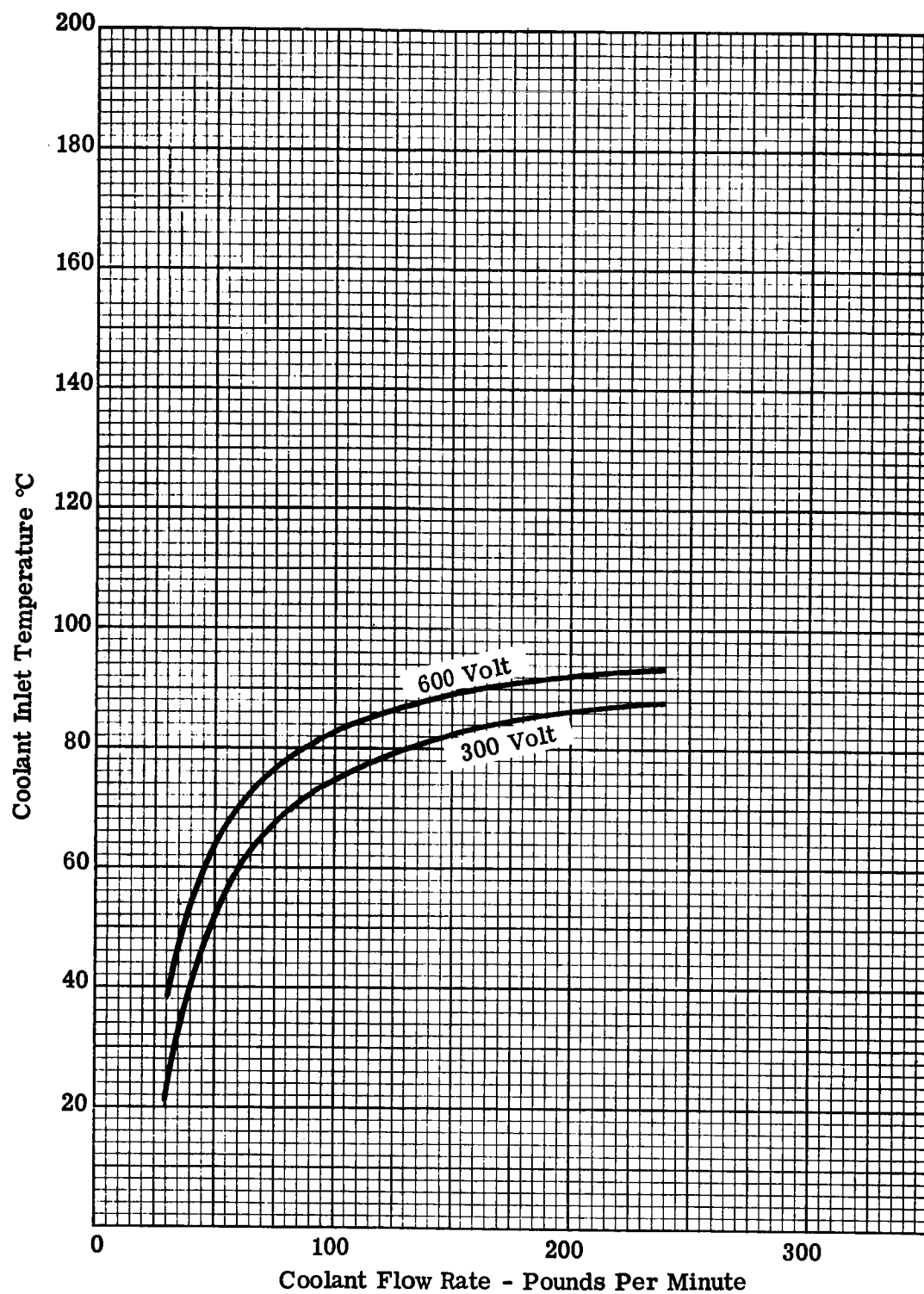


FIGURE 18

Inverter

SCR, One Megawatt, 1000 Cycles Per Second
Coolant Inlet Temperature Vs. Coolant Flow Rate

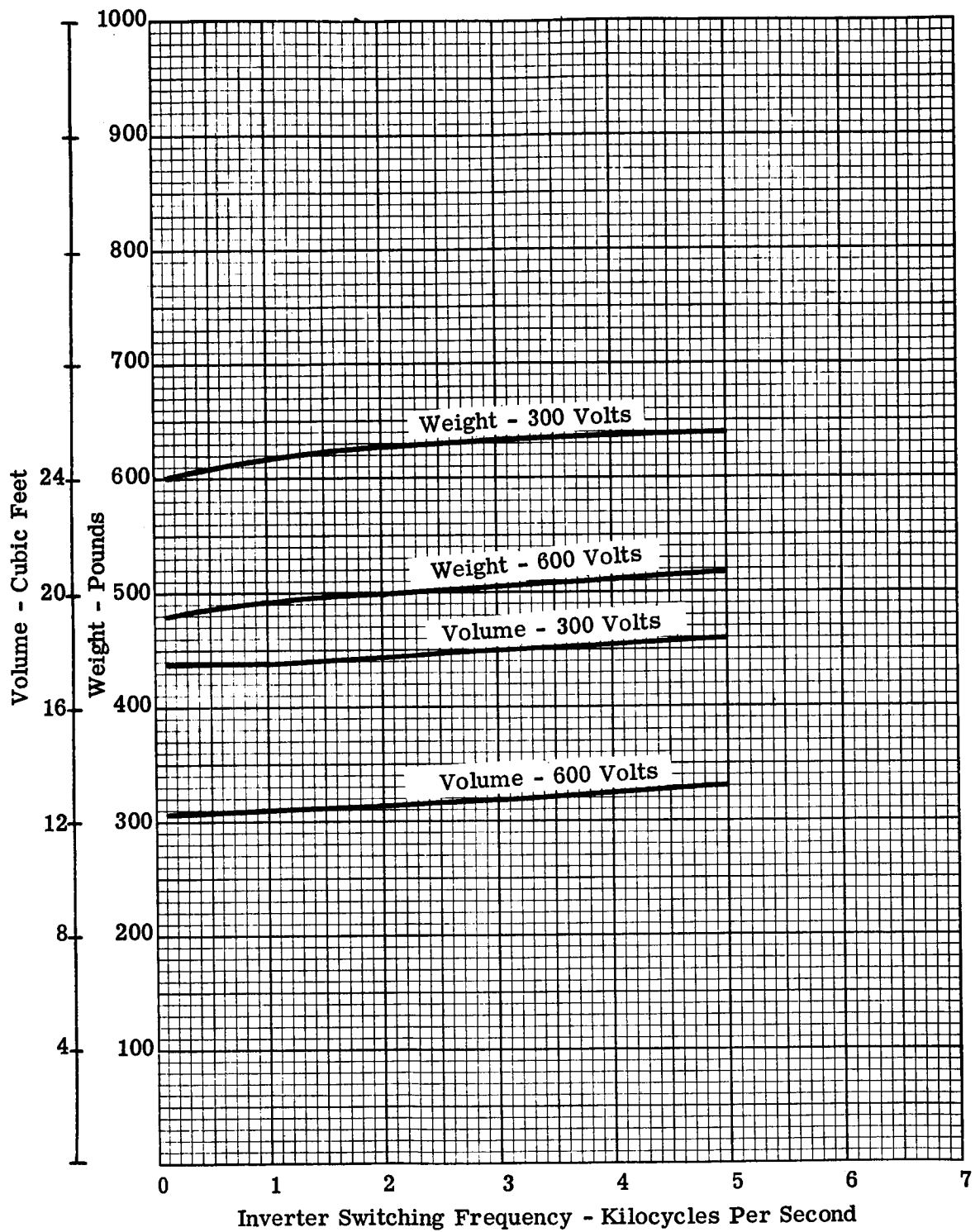


FIGURE 19

Inverter
SCR, One Megawatt
Weight And Volume Vs. Inverter Switching Frequency

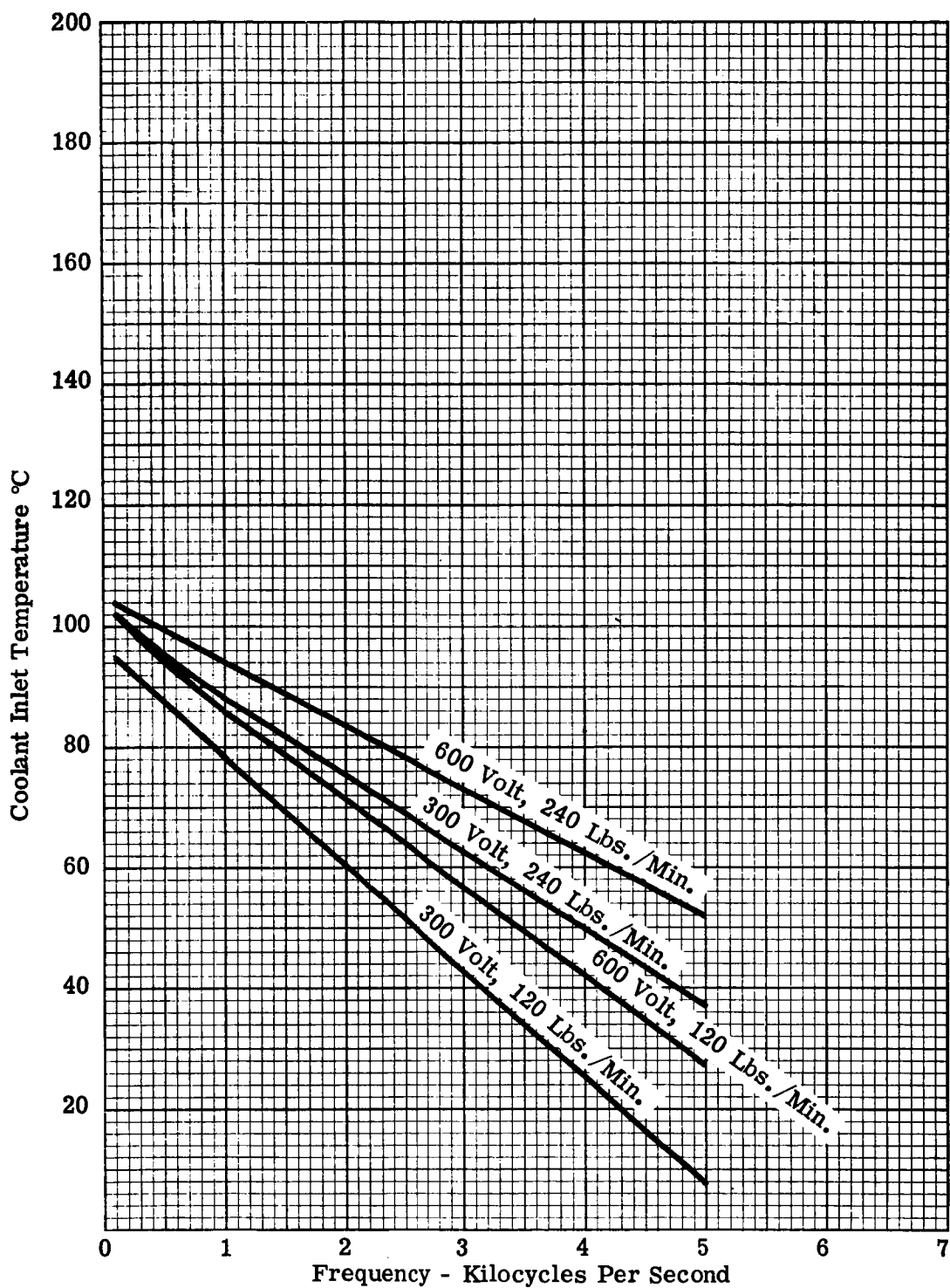


FIGURE 20
Inverter
SCR, One Megawatt
Coolant Inlet Temperature vs. Inverter Switching Frequency

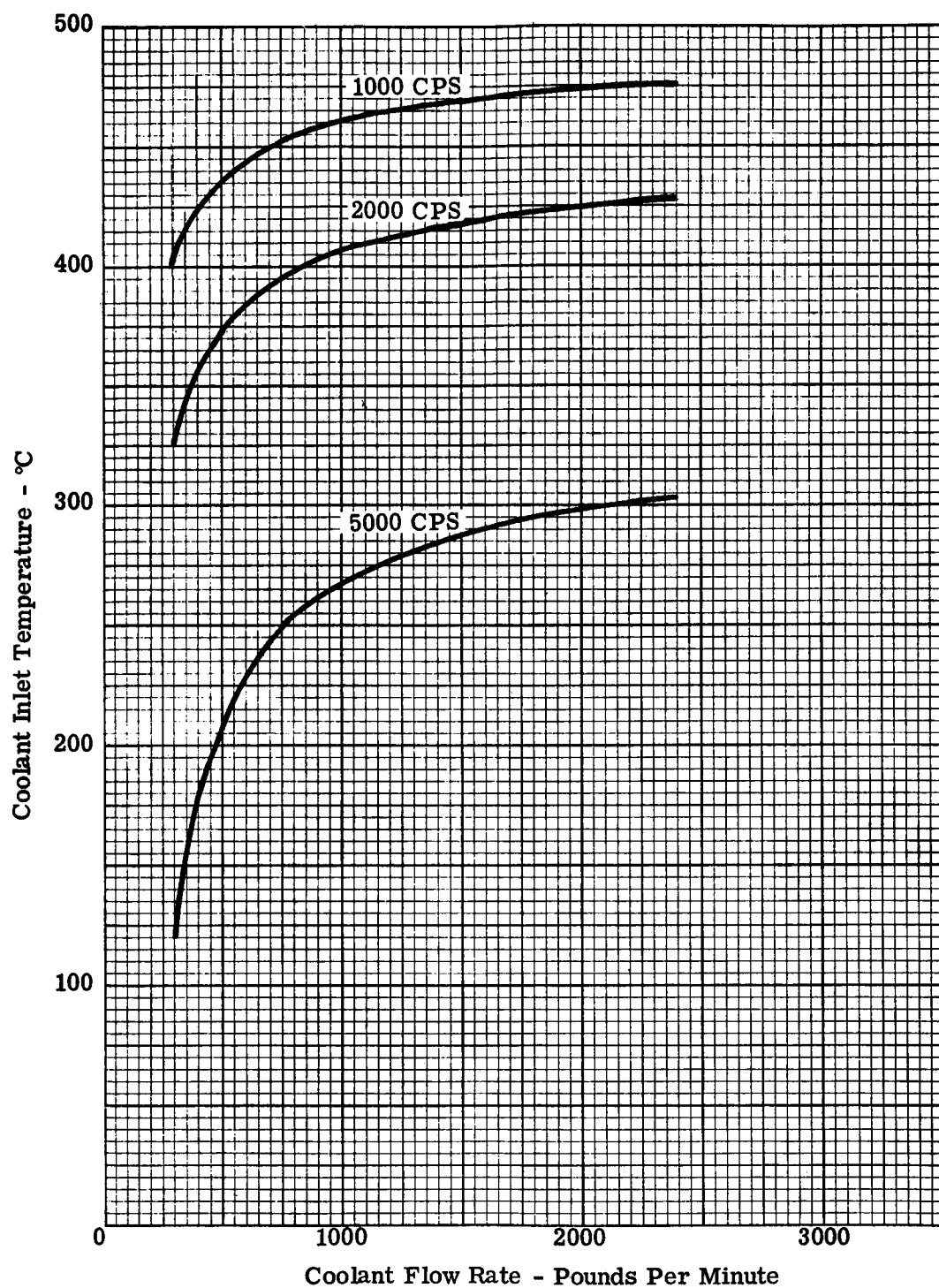


FIGURE 21

Inverter
High Temperature Design With Low Temperature Inductors
Coolant Inlet Temperature Vs. Coolant Flow Rate
For Vapor Tube Thyratrons

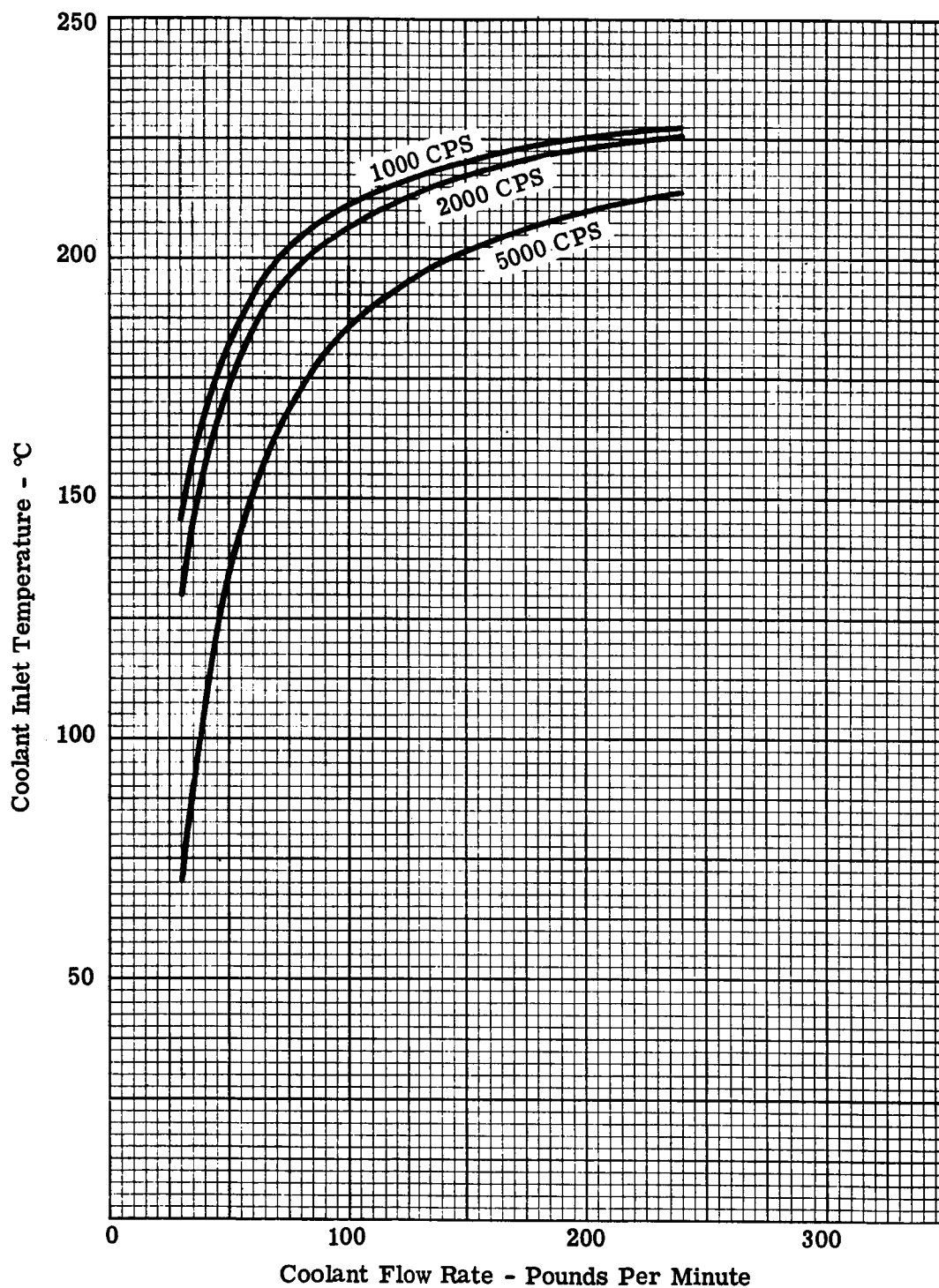


FIGURE 22

Inverter

High Temperature Design With Low Temperature Inductors
Coolant Inlet Temperature Vs. Coolant Flow Rate
For Inductors And Other Low Temperature Components

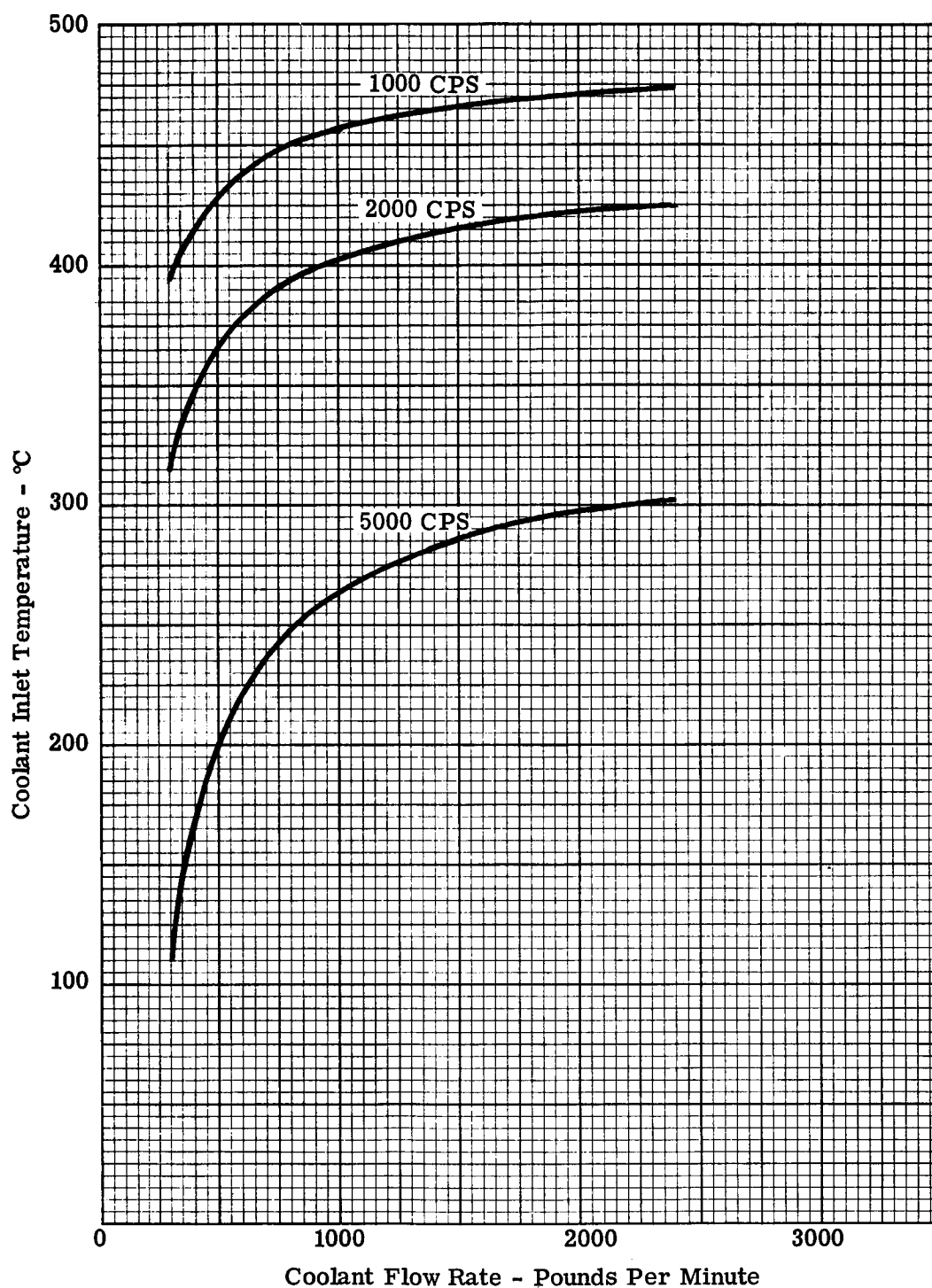


FIGURE 23
Inverter
High Temperature Design With High Temperature Inductors
Coolant Inlet Temperature Vs. Coolant Flow Rate
For Thyratrons And Inductors

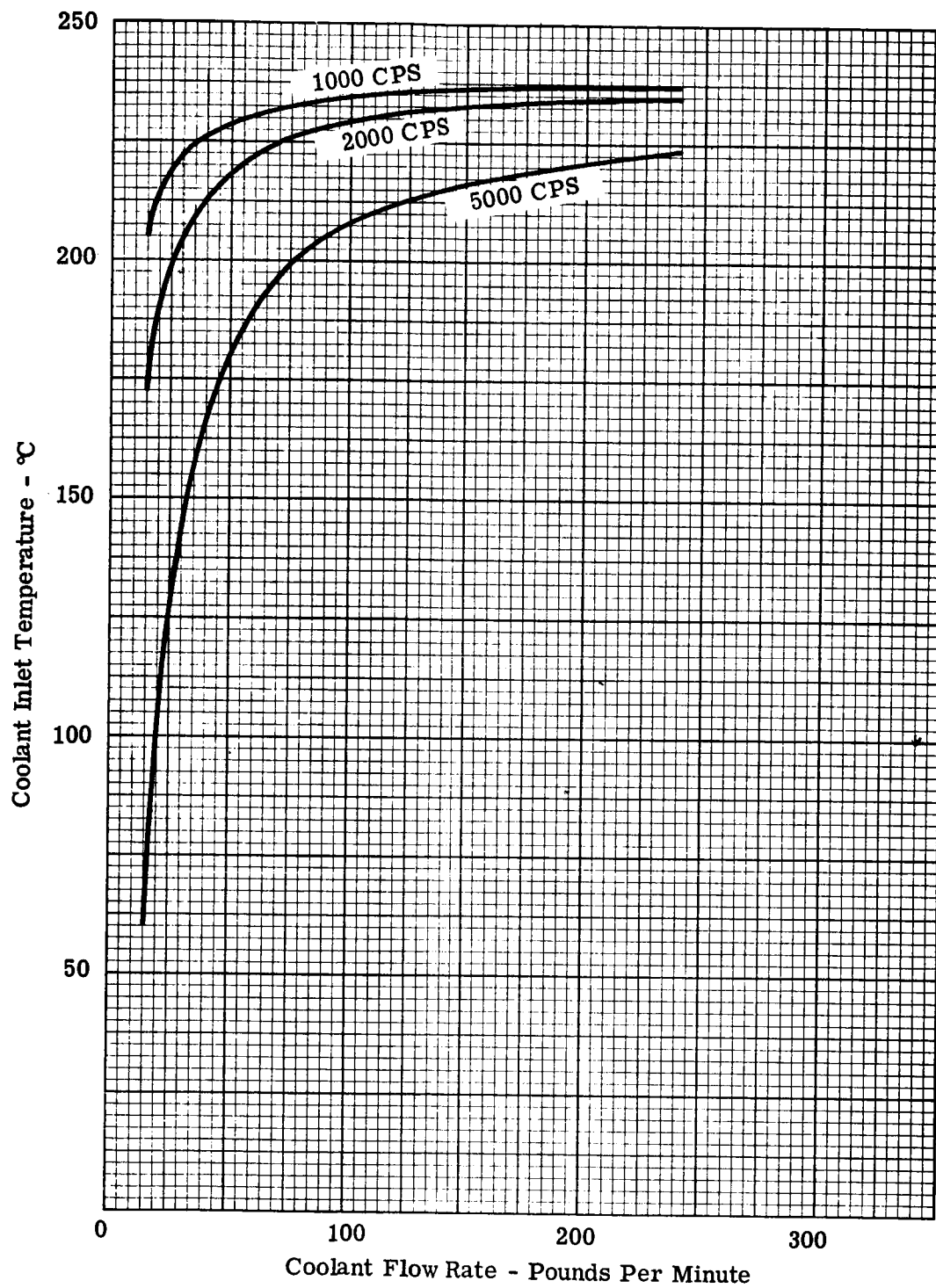


FIGURE 24

Inverter

High Temperature Design With High Temperature Inductors
Coolant Inlet Temperature Vs. Coolant Flow Rate
For Low Temperature Components

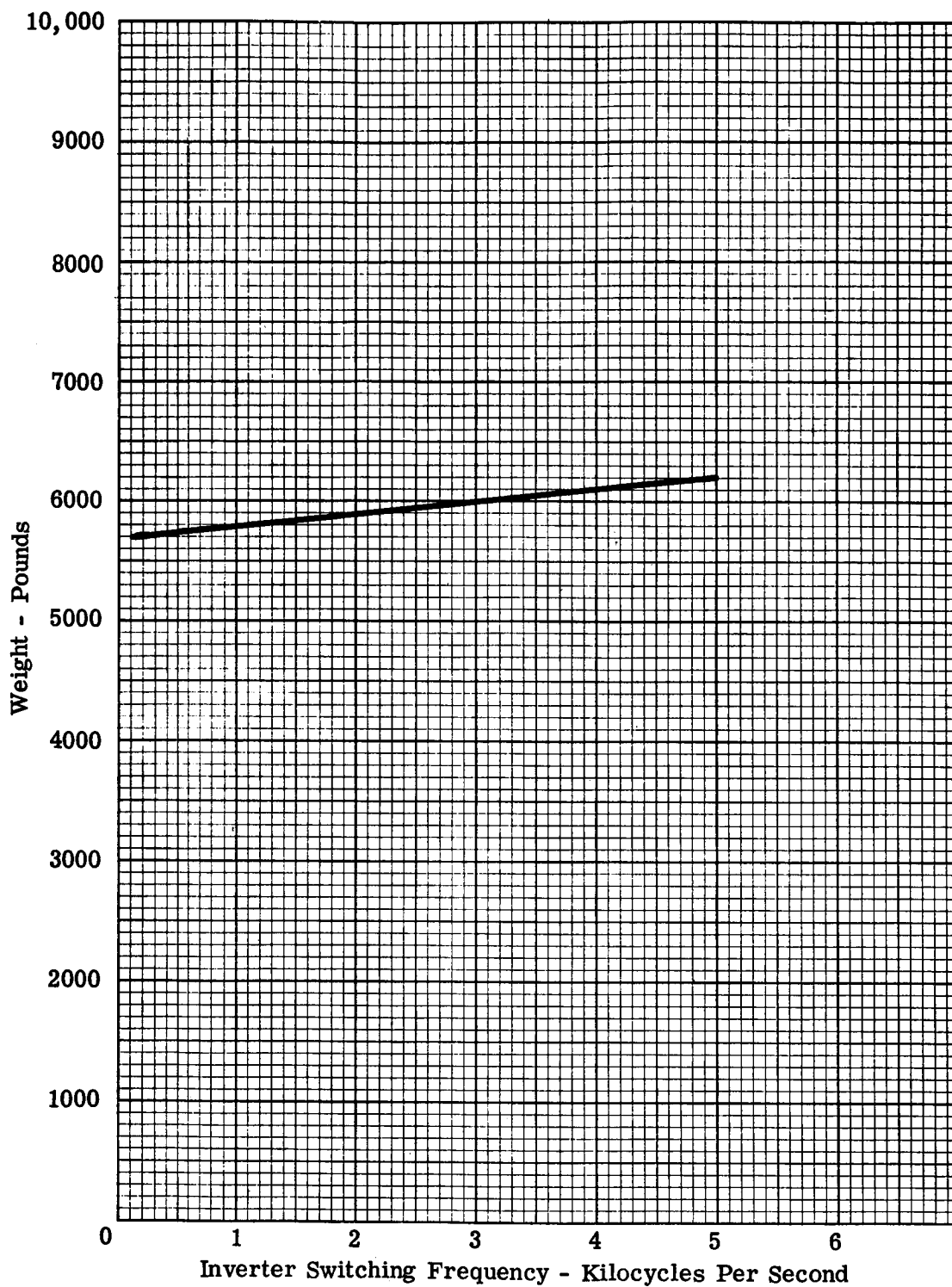


FIGURE 25

Inverter
High Temperature Design
Weight vs. Inverter Switching Frequency

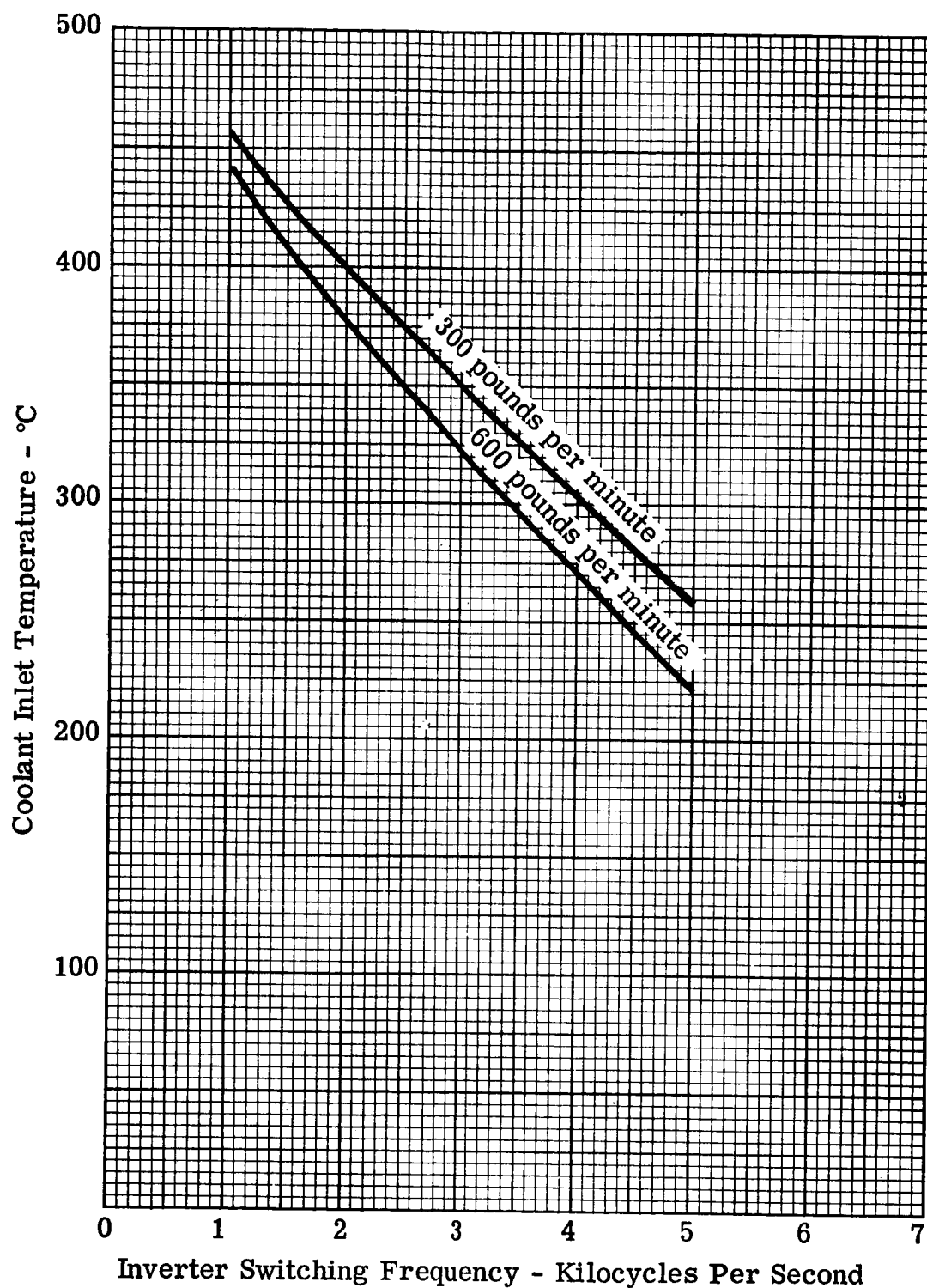


FIGURE 26

Inverter
High Temperature Design With High Temperature Inductors
Coolant Inlet Temperature Vs. Inverter Switching Frequency
For High Temperature Coolant Circuit

Problem Areas

1. A major problem area which requires development effort is in the use of beryllium for coolant tubes and cold plate. Reliable techniques for forming and joining beryllium to other metals which might be used in a complete power system cooling loop must be developed.
2. Development of reliable adhesive bonds is required for use in a space environment. Bonds should be either sufficiently elastic to relieve thermal expansion differentials, or strong enough to resist thermal stresses created between materials of different relative expansions.
3. Effort is required to develop reliable techniques in the use of titanium for the liquid metal cooling loop in the high temperature inverter design.

Analysis and Recommendation

From comparison of inverter circuit parameters, the 600-volt, one and two-megawatt systems have the lowest specific weight of any of the designs considered and appear most attractive. However, final choice of a design point must depend on consideration of all of the electrical and mechanical parameters of the complete power system.

For the 300- and 600-volt, one-megawatt design, the effect of coolant flow rate on inlet temperature is given at 1000 cycles per second and variations of weight, volume, and coolant temperature with frequency are presented. From the curve of coolant inlet temperature versus flow rate, a coolant flow of 90 to 120 pounds per minute is recommended.

Variation of weight and volume with frequency is small and of little consequence. Losses, however, as noted in Tables 10 and 13, increase with frequency quite rapidly. As a result, for constant flow rate, the required coolant inlet temperature falls substantially, and for constant temperature the required coolant flow rises substantially. Thus, the use of lower frequencies for inverter switching circuit design provides the advantages of easier cooling.

Inverter circuits using vapor tube rectifiers are substantially larger and heavier than circuits using silicon devices, as indicated in Table 12, and also yield higher total losses, as indicated in Table 10. However, the difference in shield weight must be considered in making a final system selection.

Where commutating inductors are mounted on the high temperature cooling circuit, some advantages may be gained by the reduced losses to be removed at low temperature and the high allowable coolant temperature for the remainder of the assembly. This is

indicated in Table 13 and Figures 23 and 24. Where inductors are included in the low temperature cooling circuit, on the other hand, the losses from low temperature components alone in the vapor tube system are greater than the total losses from either the 300 or 600 volt silicon semiconductor inverter circuits.

Effects of frequency on high temperature inverter circuit weight and coolant inlet temperature are similar to those for the low-temperature designs using silicon devices.

In summary, the use of silicon-controlled-rectifier-inverter circuits is recommended, with the 300-and 600-volt, 1-and 2-megawatt designs most desirable.

The use of beryllium is strongly recommended for coolant tubes and cold plate at coolant temperatures below 200 C to achieve a lower weight system. A program should be implemented to develop reliable forming and joining techniques for beryllium.

C. POWER TRANSFORMERS

This report presents the inverter power transformer parametric data generated during this study. A description of the transformer types, the thermal and mechanical design criteria, and the assumptions used to prepare the parametric data are presented.

Complete power transformer assemblies are made up of appropriate numbers of individual transformer units. Two methods of combining were studied. First, by series secondaries; second, by threading a common secondary through all like cores (See Figure 27).

The parametric data for all transformer units is based on copper conductors and tape-wound cores of silicon iron for the magnetic material. Weights given in this part of the report are electromagnetic weights.

A set of curves is presented, showing in general, how weight and losses vary with frequency and how weight and losses vary with transformer kva rating. In addition, tabulated parametric data is presented for each system studied. All tabulated data refers to 400-cycle frequency, but may be converted to other frequencies by means of the curves.

Electrical Design

Description

The power transformers are single-phase shell type. The primary winding is center tapped while the secondary is a single winding. The transformers used in conjunction with the unregulated inverter modules are of conventional design, whereas the transformers used with the regulated inverter modules have oversize cores. The oversize cores are needed to withstand two successive half-cycles of voltage in the same direction, which are applied to the transformer when its respective inverter module is turned on or off to regulate system output voltage.

Design Criteria

In the design of the inverter power transformers a number of assumptions were made and conditions standardized to show effects of the variable conditions.

1. Conductor is copper and losses are based on 100% conductivity, standard annealed copper at 500°C.
2. As little data is available on losses of iron with a square wave input, characteristics are assumed to be the same as for a sine wave input.

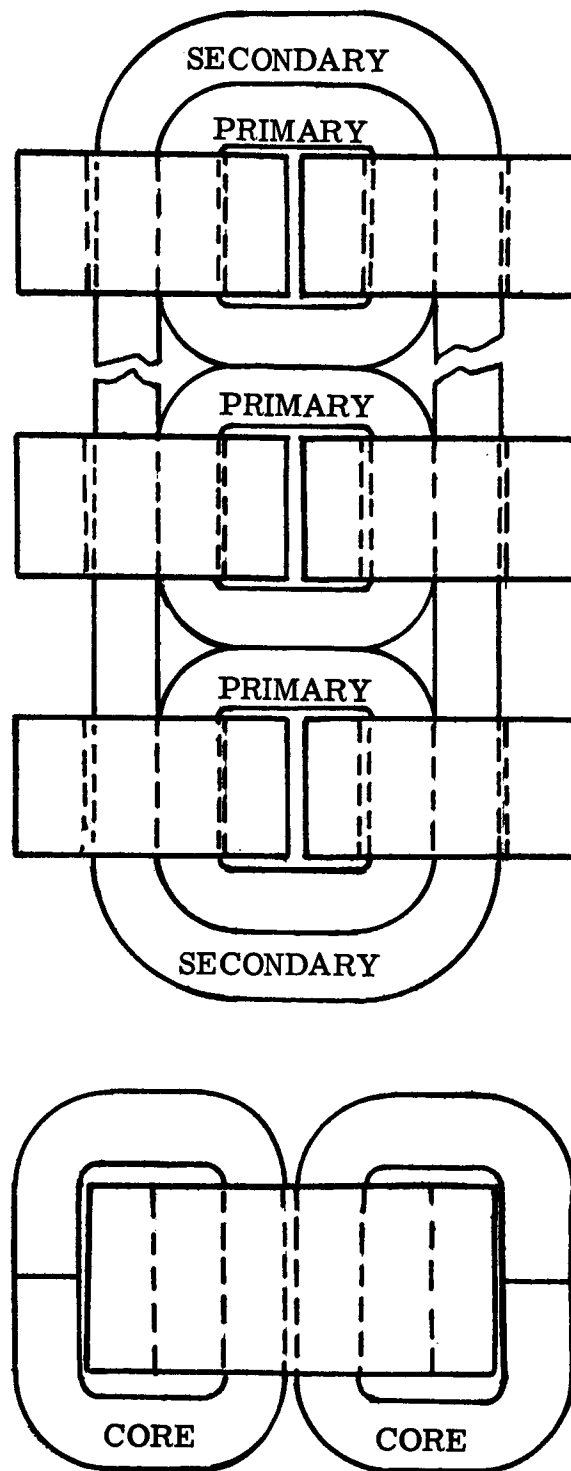


FIGURE 27
Common - Secondary Transformer Diagram

3. Insulation was provided for the dielectric requirements based on 100 volts per mil through the insulation and 25 volts per mil creepage. Windings that operate at 20 KV were designed for complete coverage by insulation.
4. The temperature rise characteristics of the individual designs are maintained at approximately the same level.
5. Individual transformer designs are made at a frequency of 400 cycles per second for each of the different systems, and one design is carried through the range of 50-5000 cycles per second to determine the effect of frequency on weight and losses.

Parametric Data

Table 14 lists the individual inverter power transformer ratings studied and presents the weight and losses at 400 cycles per second. Tables 15 through 18 list the ratings of the individual units, quantities, losses, and weights for all of the different system ratings at 400 cycles per second. The curve of Figure 28 shows variation of weight and losses for individual inverter power transformers for frequencies from 50 to 5000 cycles per second. The curve of Figure 29 shows variation of weight and losses per kva for different kva ratings. Figure 30 shows heat loads of complete power transformer assemblies for the different system power ratings, at a frequency of 400 cycles per second. Figure 31 shows transformer efficiency at different input voltages.

Problem Areas

The manufacture of transformers to operate at extremely high temperatures (600°C) with high reliability and with extended service life involves several unknown factors. The useful life of a transformer is greatly reduced when operating temperature is increased. Little is known of service life and dielectric strength of insulating materials at elevated temperatures.

Analysis and Recommendations

As seen from Figure 29, there is a savings in weight and a large savings in losses in the inverter power transformer assembly when using individual transformers of the higher kva ratings. Figure 28 shows the weight and losses are further reduced by having the system operate at a higher frequency. To keep weight and losses low the higher kva ratings and higher frequencies should be used. The optimum frequency depends on a complete analysis of the power conversion system.

TABLE 14

POWER TRANSFORMER WEIGHTS AND LOSSES

Transformers Insulated for 5 KV Bus Voltage				
For Unregulated Modules			For Regulated Modules	
Rating (kva)	Losses (watts)	Weight (pounds)	Losses (watts)	Weight (pounds)
1	100	2.084	131	3.12
5	266	8.18	345	12.25
23	632	34	820	51.0
29	723	43.6	950	65.5
46	990	64.7	1280	97.0
Transformers Insulated for 20 KV Bus Voltage				
1	104	2.26	133	3.40
5	276	8.89	350	13.35
46	995	70.3	1270	106.0

Note: All Figures Refer to 400 cps.

All Weights are Electromagnetic Weights.

TABLE 15

POWER TRANSFORMER ELECTRICAL PARAMETRIC DATA
0.5 MEGAWATT SYSTEMS

Transformer Rating (kva)	1	5	23	23
Input Voltage (volts)	20	100	300	600
Unregulated Designs				
Number Units	412	80	18	18
Losses (total watts)	41,200	21,300	11,400	11,400
Weight (pounds)	860	652	612	612
Regulated Designs				
Number Units	138	30	6	6
Losses (total watts)	18,100	10,350	4,920	4,920
Weight (pounds)	430	367	306	306
System Totals				
Individual Secondaries				
Losses (watts)	59,300	31,650	16,320	16,320
Weight (pounds)	1290	1019	918	918
System Totals				
Common Secondaries				
Losses (watts)	48,650	27,110	14,600	14,600
Weight (pounds)	1220	950	860	860

Note: All Figures Refer to 400 cps.

All Weights are Electromagnetic Weights.

TABLE 16

POWER TRANSFORMER ELECTRICAL PARAMETRIC DATA
FOR 1.0 MEGAWATT SYSTEMS

Transformer Rating (kva)	1	5	46	46
Input Voltage (volts)	20	100	300	600
Unregulated Designs				
Number Units	824	160	18	18
Losses (total watts)	82,400	42,600	17,800	17,800
Weight (pounds)	1720	1304	1165	1165
Regulated Designs				
Number Units	276	60	6	6
Losses (total watts)	36,200	20,000	7,680	7,680
Weight (pounds)	860	735	582	582
System Totals				
Individual Secondaries				
Losses (watts)	118,600	62,600	25,480	25,480
Weight (pounds)	2580	2039	1747	1747
System Totals				
Common Secondaries				
Losses (watts)	97,300	54,220	22,800	22,800
Weight (pounds)	2440	1897	1635	1635

Note: All Figures Refer to 400 cps.

All Weights are Electromagnetic Weights.

TABLE 17

POWER TRANSFORMER ELECTRICAL PARAMETRIC DATA
FOR 2 MEGAWATT SYSTEMS

Transformer Rating (kva)	1	5	46	46
Input Voltage (volts)	20	100	300	600
Unregulated Designs				
Number Units	1648	326	36	36
Losses (total watts)	171,500	90,000	35,800	35,800
Weight (pounds)	3725	2900	2570	2510
Regulated Designs				
Number Units	552	114	12	12
Losses (total watts)	73,500	40,900	15,500	15,500
Weight (pounds)	1880	1520	1284	1284
System Totals				
Individual Secondaries				
Losses (watts)	245,000	130,900	51,300	51,300
Weight (pounds)	5610	4420	3854	3854
System Totals				
Common Secondaries				
Losses (watts)	203,000	115,500	46,500	46,500
Weight (pounds)	5300	4070	3600	3600

Note: All Figures Refer to 400 cps.

All Weights are Electromagnetic Weights.

TABLE 18

POWER TRANSFORMER ELECTRICAL PARAMETRIC DATA
FOR 5 MEGAWATT SYSTEMS

Transformer Rating (kva)	1	5	29	29
Input Voltage (volts)	20	100	300	600
Unregulated Design				
Number Units	3890	778	136	136
Losses (Total Watts)	389,000	207,000	99,500	99,500
Weight (pounds)	8120	6360	5930	5930
Regulated Design				
Number Units	1610	322	56	56
Losses (Total Watts)	211,000	111,000	44,000	44,000
Weight (pounds)	5025	3945	3070	3070
System Totals				
Individual Secondaries				
Losses (watts)	600,000	318,000	143,500	143,500
Weight (pounds)	13,145	10,305	9000	9000
System Totals				
Common Secondaries				
Losses (watts)	495,000	275,000	127,000	127,000
Weight (pounds)	12,430	9580	8050	8050

Note: All Figures Refer to 400 cps.

All Weights are Electromagnetic Weights.

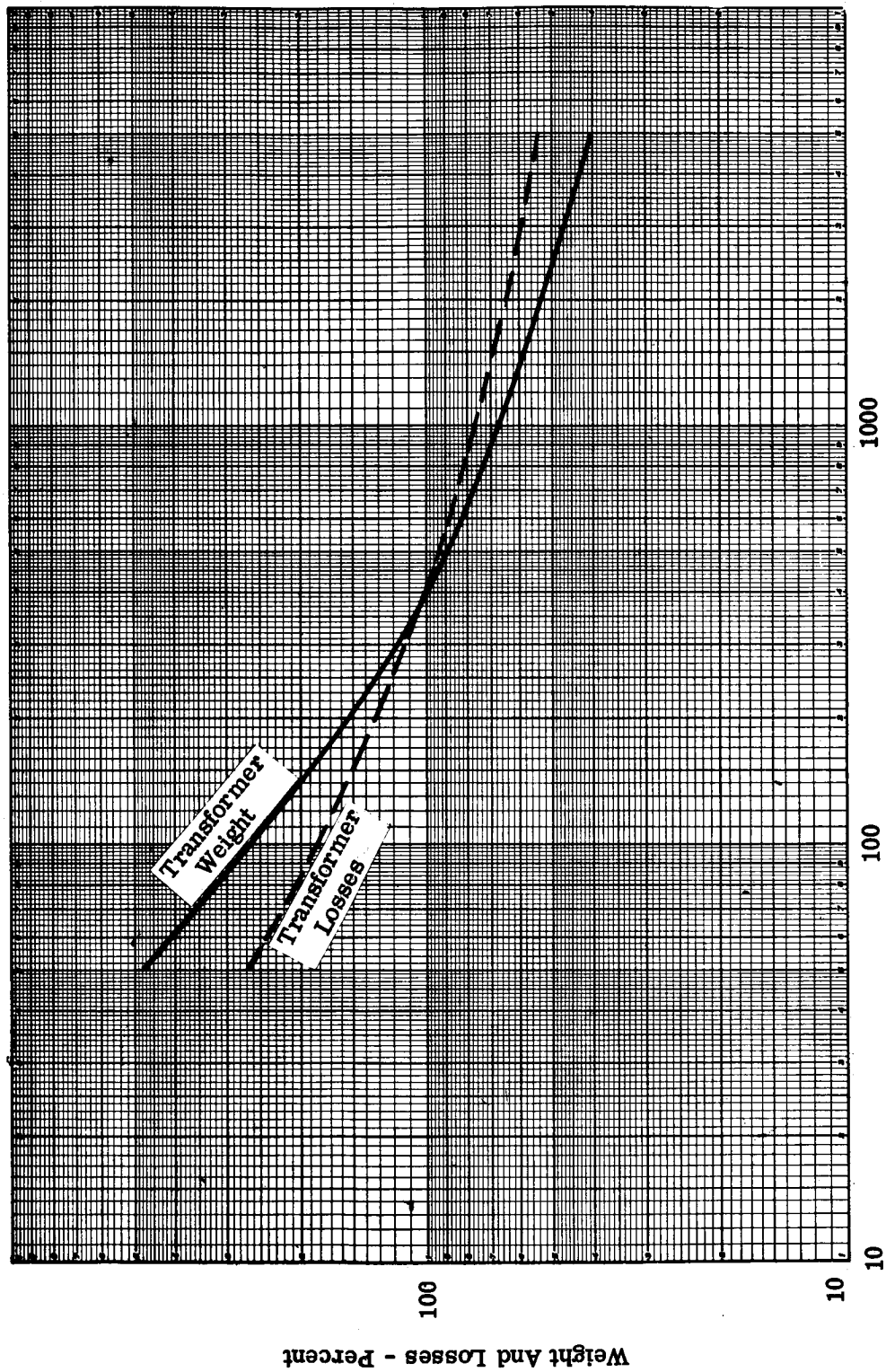


FIGURE 28
Inverter Switching Frequency - Cycles Per Second

Transformer
Shell Type
Relative Weight and Losses Vs. Inverter Switching Frequency

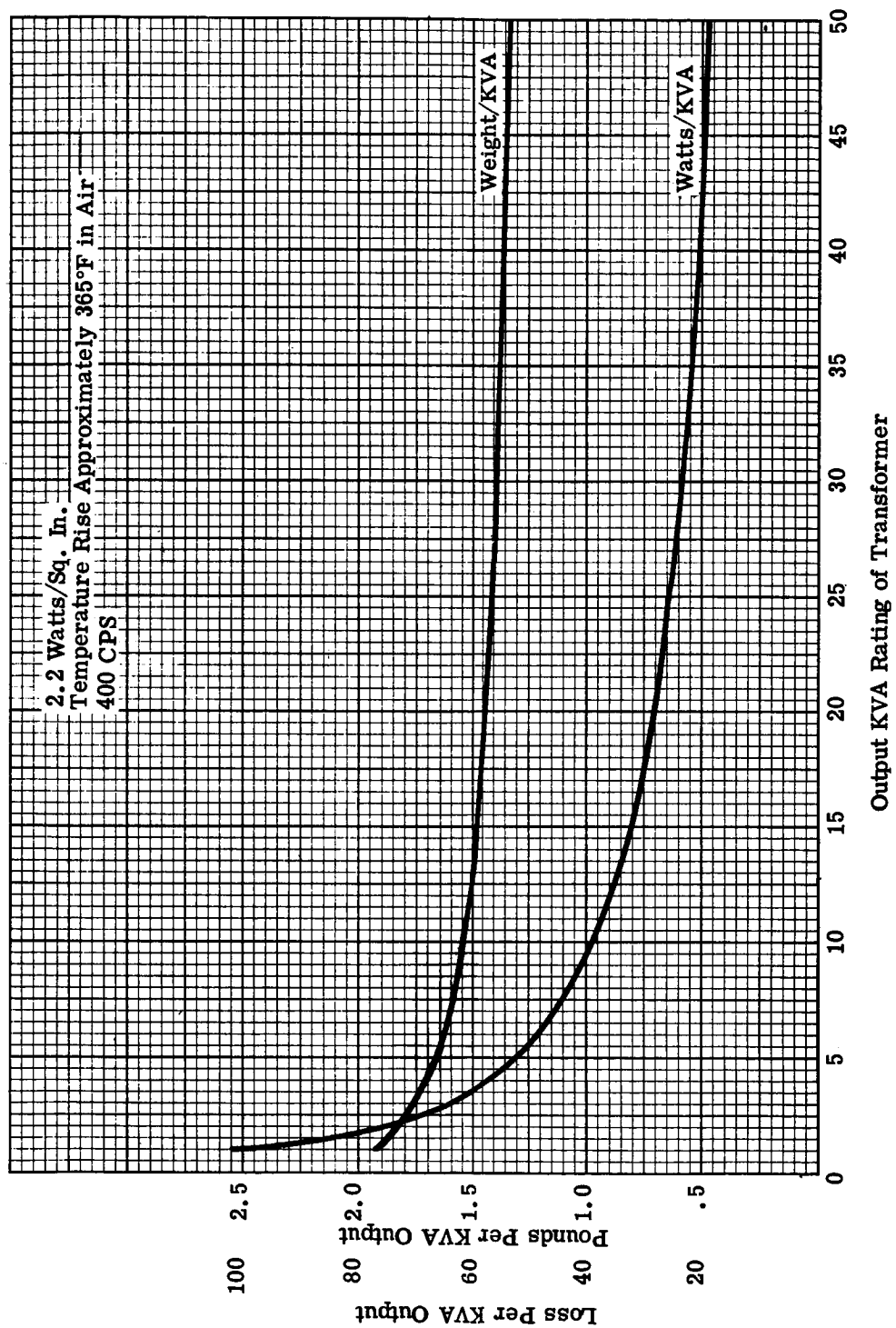


FIGURE 29
Transformer
Shell Type
Specific Weight and Losses Per KVA Vs. KVA Rating

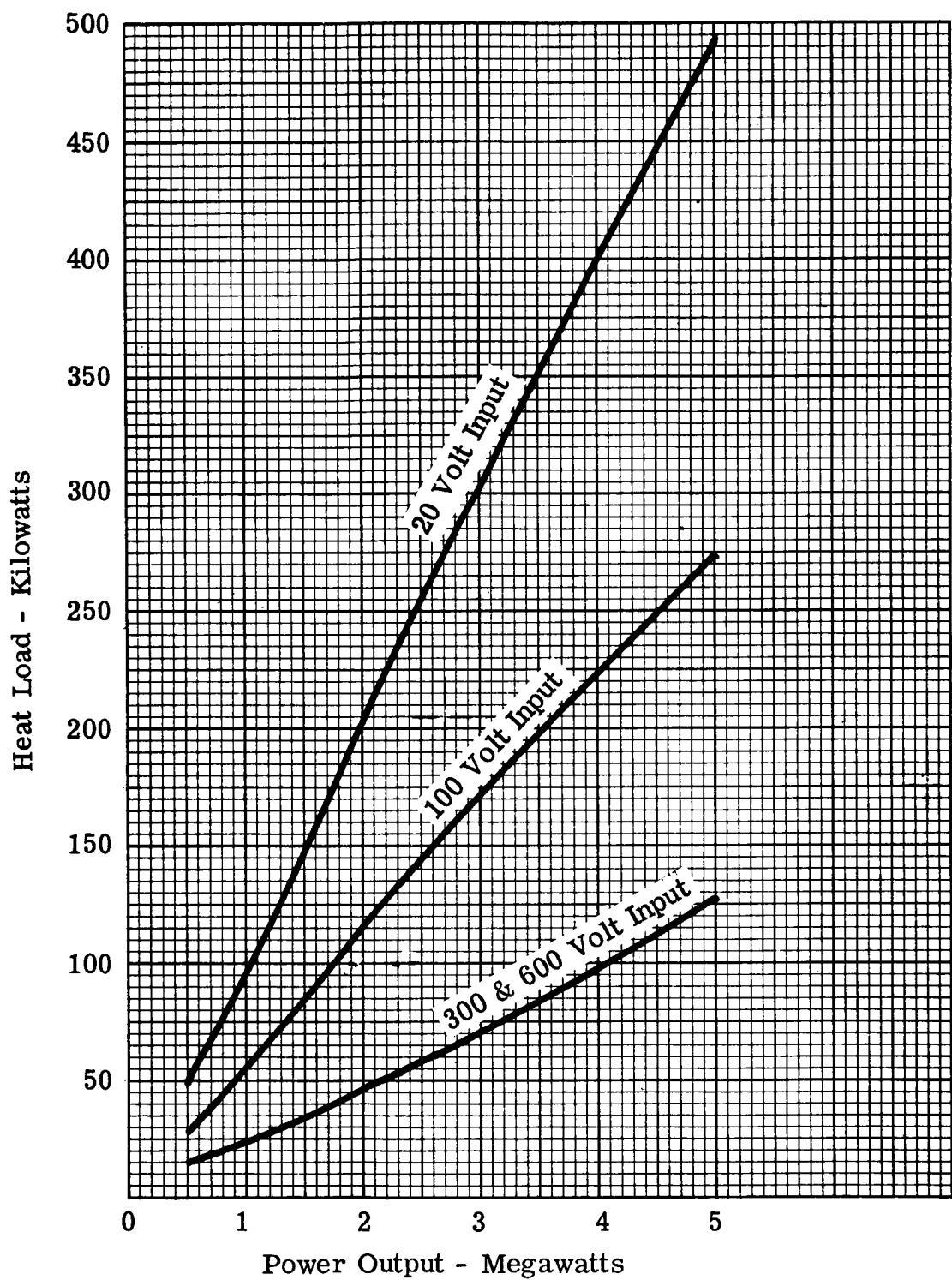


FIGURE 30
Transformer
400 Cycles Per Second
Heat Loads Vs. Power Output

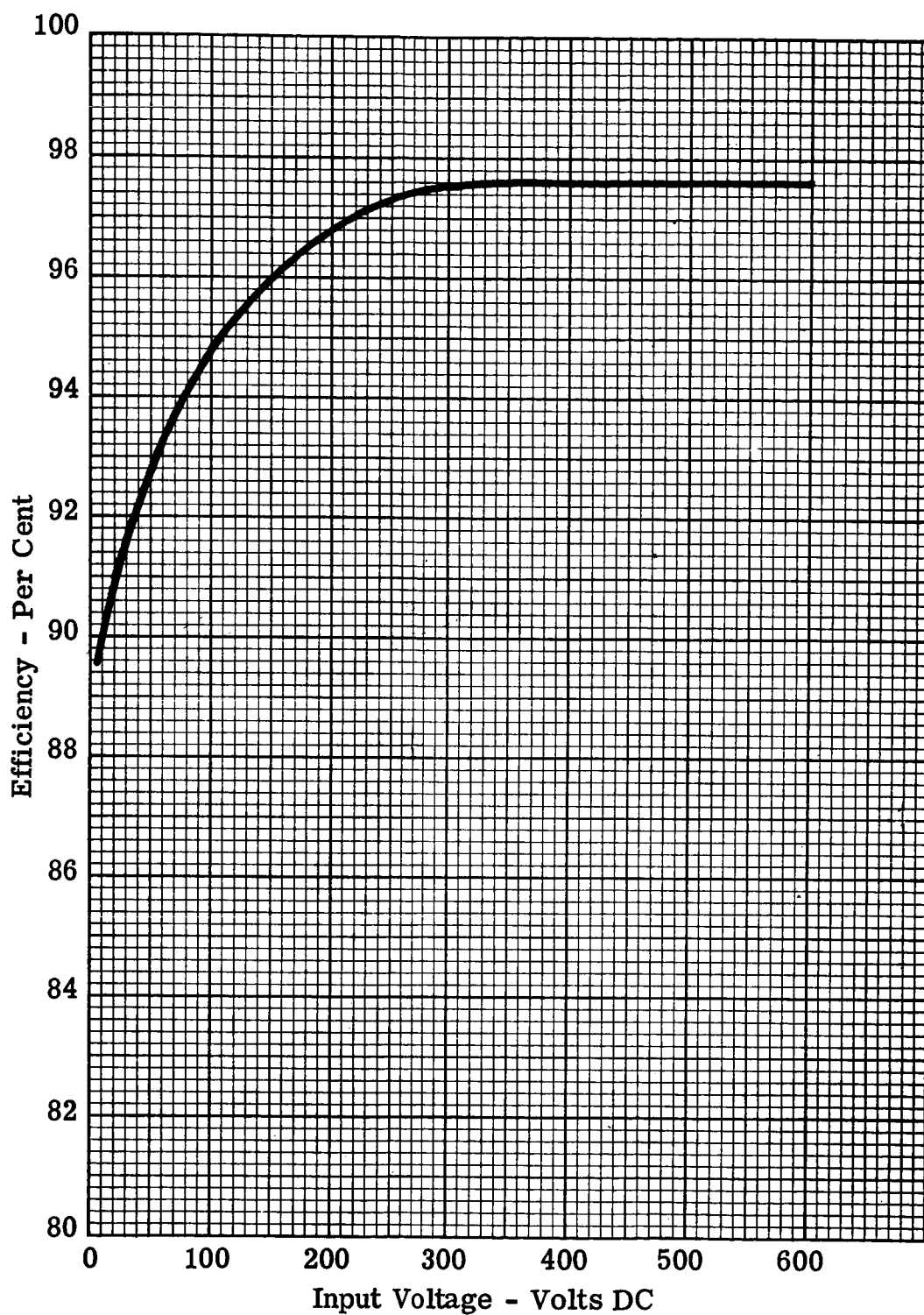


FIGURE 31
Transformer
400 Cycles Per Second
Efficiency Vs. Input Voltage

Insulating materials should be tested and evaluated at elevated temperatures to determine their dielectric strength and service characteristics. Magnetic materials should be investigated and loss characteristics determined for square wave voltages.

Because conductor resistance and losses at 600°C are approximately 75% higher than at 250°C, careful analysis must be made to determine whether the higher operating temperatures are desirable. Lower operating temperatures result in higher system efficiencies with possible lighter weight equipment and lighter or equivalent cooling system weights.

Mechanical Design

Description

The complete power transformer assembly for each inverter design consists of an appropriate number of smaller rated transformer units. The construction used for mechanical design purposes includes a common secondary threaded through a number of shell-type cores with an individual primary wound on each core. In general, a common secondary was assumed for each 6 or 18 primary windings.

This type of construction requires that the cores be stacked parallel to each other. Coolant conduits and cooling straps are integral parts of the structure that supports the cores. Transformers are potted to facilitate heat removal. Eutectic NaK is used as a coolant. Coolant conduits and structure are of columbium.

Design Criteria

The following basic design criteria were used in calculating the required parametric data:

1. The coolant is eutectic NaK, having a specific heat of 0.210 Btu/lbs-°F, and a density of 0.0306 lbs/in.³. Convection temperature drop is 1°C.
2. Columbium for use in coolant conduits and structure has the following characteristics:

Density	0.310 lbs/in ³
Thermal Conductivity	31.5 Btu/hr-ft-°F
Thermal Expansion	3.82 x 10 ⁻⁶ in/in/°F

3. The total weight of each transformer assembly is 1.9 times the electromagnetic weight. This is based on previous studies in which the total weight varied from 1.7 to 2.05 times the electromagnetic weight.

4. The maximum transformer hot spot temperature is assumed to 550°C . Internal temperature rise is assumed to be 150°C .

Parametric Data

Total transformer weights are presented in Table 19 for various power ratings, voltage, and frequencies. Specific weight in pounds per kilowatt is also presented at 400 cycles per second. Total transformer volumes are presented in Table 20. Parameters are also described by curves in Figures 32 through 36 for the power transformers.

Figures 32 and 33 present variation of transformer total weight and volume respectively with converter power rating for input voltages of 20, 100, 300, and 600 volts, and at a frequency of 400 cycles per second. Figures 34 and 35 give parameters for the one megawatt, 300- and 600-volt design. Figure 34 shows variation of coolant inlet temperature with flow rate at a frequency of 400 cycles per second. Figure 35 shows variation of weight and volume with frequency. Figure 36 shows variation of coolant inlet temperature with frequency at coolant flow rates of 120 and 240 pounds per minute.

Problem Areas

1. The most difficult problem anticipated is the development of transformers that will have high reliability and sufficient service life at temperatures in the order of 550 to 600°C . There is little previous experience and little known about properties of insulation at these temperatures.
2. If transformers are to be potted to aid cooling, much development is needed to obtain potting compounds which are applicable to high temperatures and a space environment.
3. Care must be taken in choice and use of materials to avoid severe thermal stresses at design temperature extremes.
4. In the event that the potting of transformers proves unfeasible for use in the design temperature range, an alternate design must be developed to allow routing of coolant directly through transformers, as described in previous work in this program.

Analysis and Recommendations

From comparison of power transformer parameters at 400 cycles per second, the 300- and 600-volt, 1- and 5-megawatt designs have the lowest specific weight of the designs considered. This trend is expected to remain true at all frequencies. The 300- and 600-volt, 1-megawatt systems were chosen as a base point for the data in

TABLE 19
POWER TRANSFORMER WEIGHT SUMMARY

Voltage Input (volts)	20	20	20	20	100	100	100	100	300, 600	300, 300, 600 600	300, 300, 600 600	
Power Output (megawatts)	0.5	1	2	5	0.5	1	2	5	0.5	1	2	5
Transformer Wt. (thousands of lbs.)												
50 cps	11.1	22.2	48.5	113	8.65	17.3	37.2	87.4	7.85	14.9	32.9	73.5
100 cps	6.15	12.25	26.8	62.5	4.77	9.55	20.5	48.3	4.33	8.22	18.15	40.5
200 cps	3.55	7.1	15.5	36.1	2.75	5.5	11.85	27.8	2.53	4.74	10.5	23.4
400 cps	2.32	4.64	10.1	23.6	1.8	3.6	7.75	18.2	1.634	3.1	6.85	15.3
1000 cps	1.57	3.13	6.82	15.9	1.215	2.43	5.23	12.3	1.095	2.09	4.62	10.3
2000 cps	1.23	2.46	5.35	12.5	.955	1.91	4.12	9.65	.865	1.64	3.63	8.12
5000 cps	.94	1.88	4.09	.955	.730	1.46	3.13	7.35	.654	1.25	2.77	6.18
Transformer Specific Wt. at 400 cps (lbs/kva)	4.64	4.64	5.05	4.72	3.60	3.60	3.88	3.64	3.23	3.10	3.43	3.06

TABLE 20
POWER TRANSFORMER VOLUME SUMMARY

Voltage Input (volts)	20	20	20	20	100	100	100	100	300, 600	300, 300, 600 600
Power Output (megawatts)	.5	1	2	5	.5	1	2	5	.5	1 2 5
TRANSFORMER VOLUME (cu. ft.)										
50 cps	5.18	104	271	528	32.7	52.8	153.1	361	26.4	44.2 112 266
100 cps	28.6	57.3	150	292	18.0	29.1	84.5	199	14.6	24.4 62.0 147
200 cps	16.5	33.0	86.4	168	10.43	16.9	49.0	115.2	84.1	14.1 35.8 84.8
400 cps	10.8	21.6	56.5	110	6.80	11.00	31.9	75.1	5.49	9.22 23.4 55.4
1000 cps	7.28	14.6	38.1	74.1	4.55	7.36	21.4	50.3	3.70	6.21 15.8 37.3
2000 cps	5.73	11.5	30.0	58.3	3.60	5.84	16.9	39.8	2.91	4.88 12.4 29.4
5000 cps	4.37	8.75	22.9	23.6	2.72	4.40	12.75	30.1	2.22	3.73 9.48 22.4

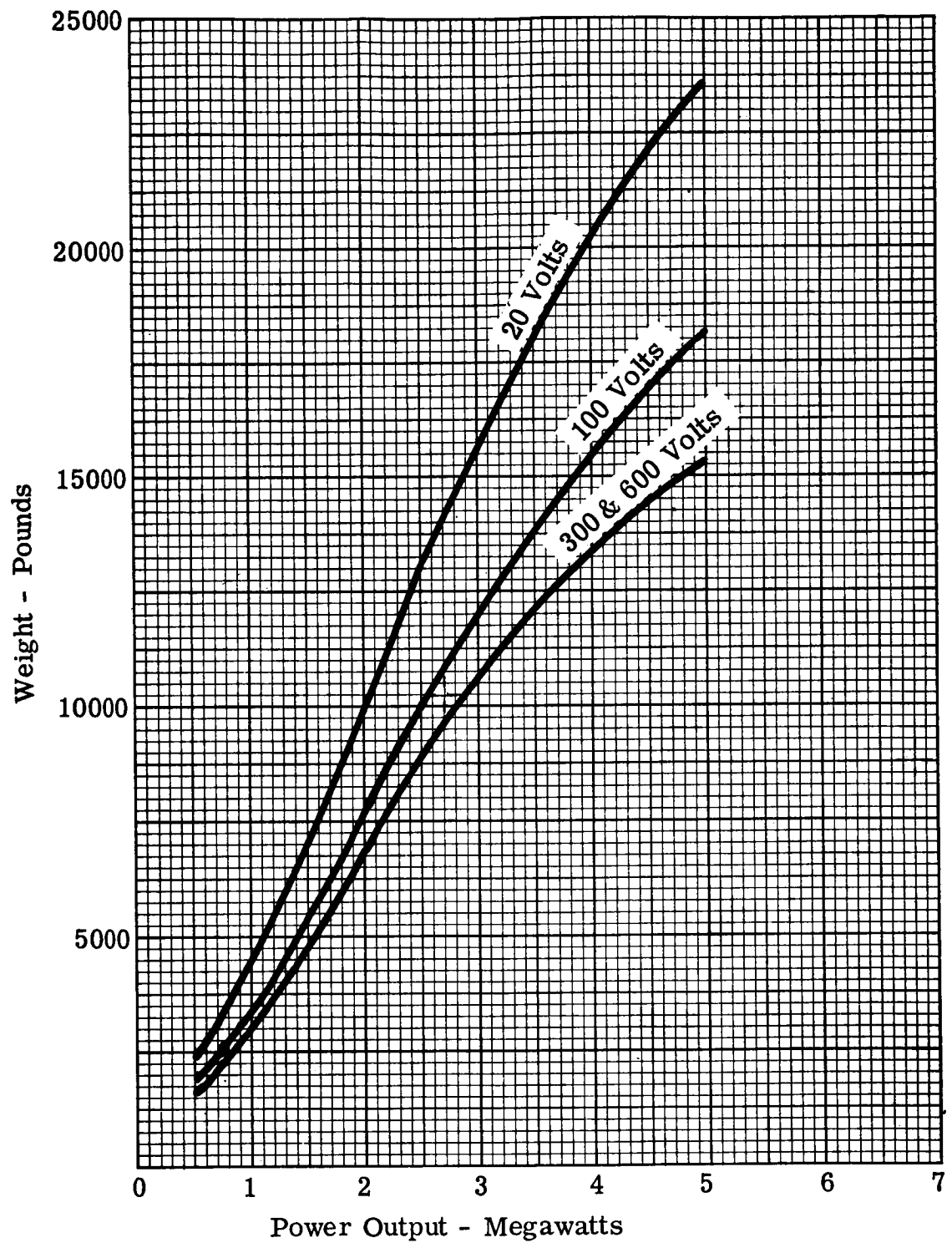


FIGURE 32
Transformer
400 Cycles Per Second
Weight Vs. Power Output

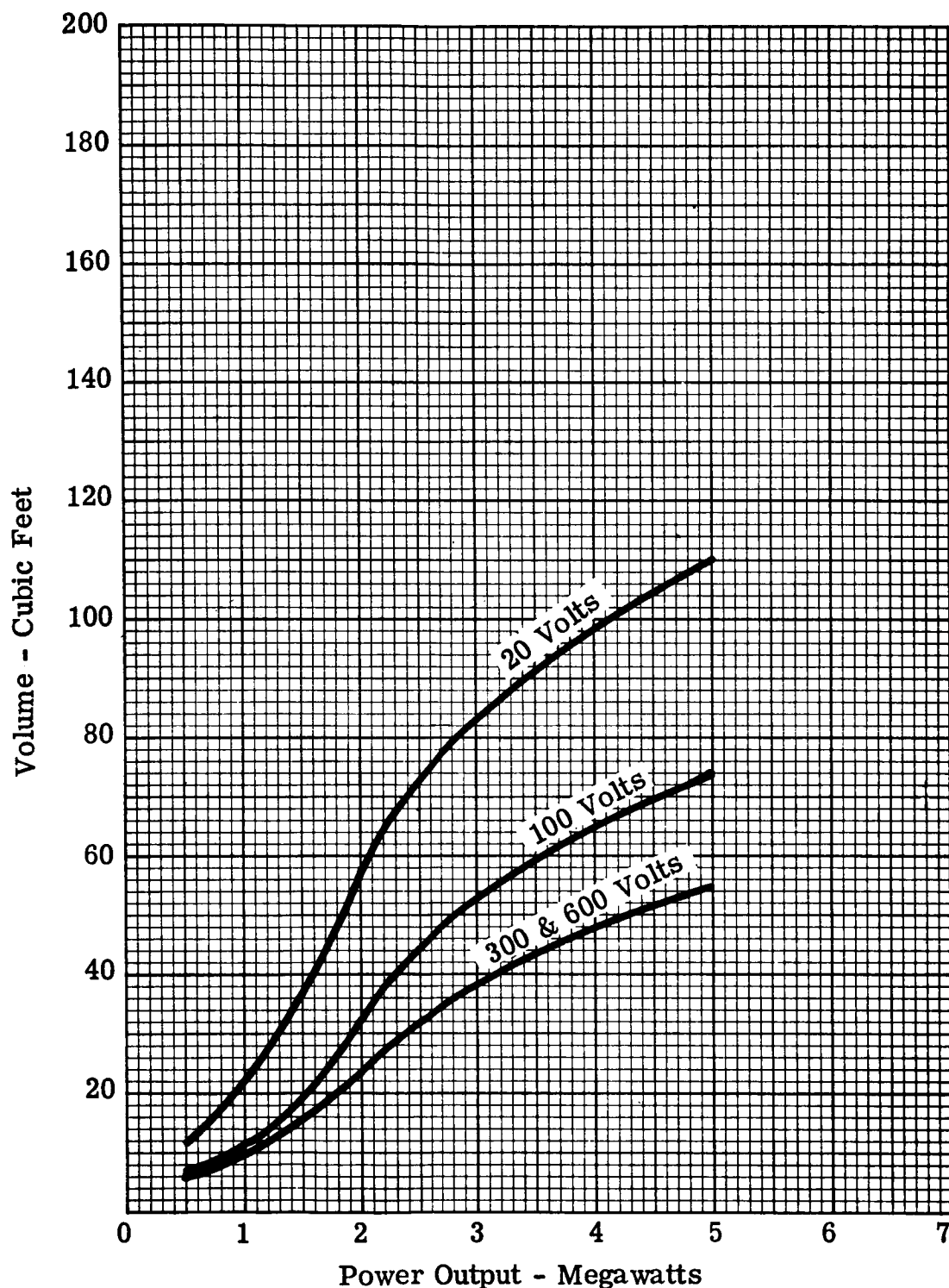


FIGURE 33
Transformer
400 Cycles Per Second
Volume Vs. Power Output

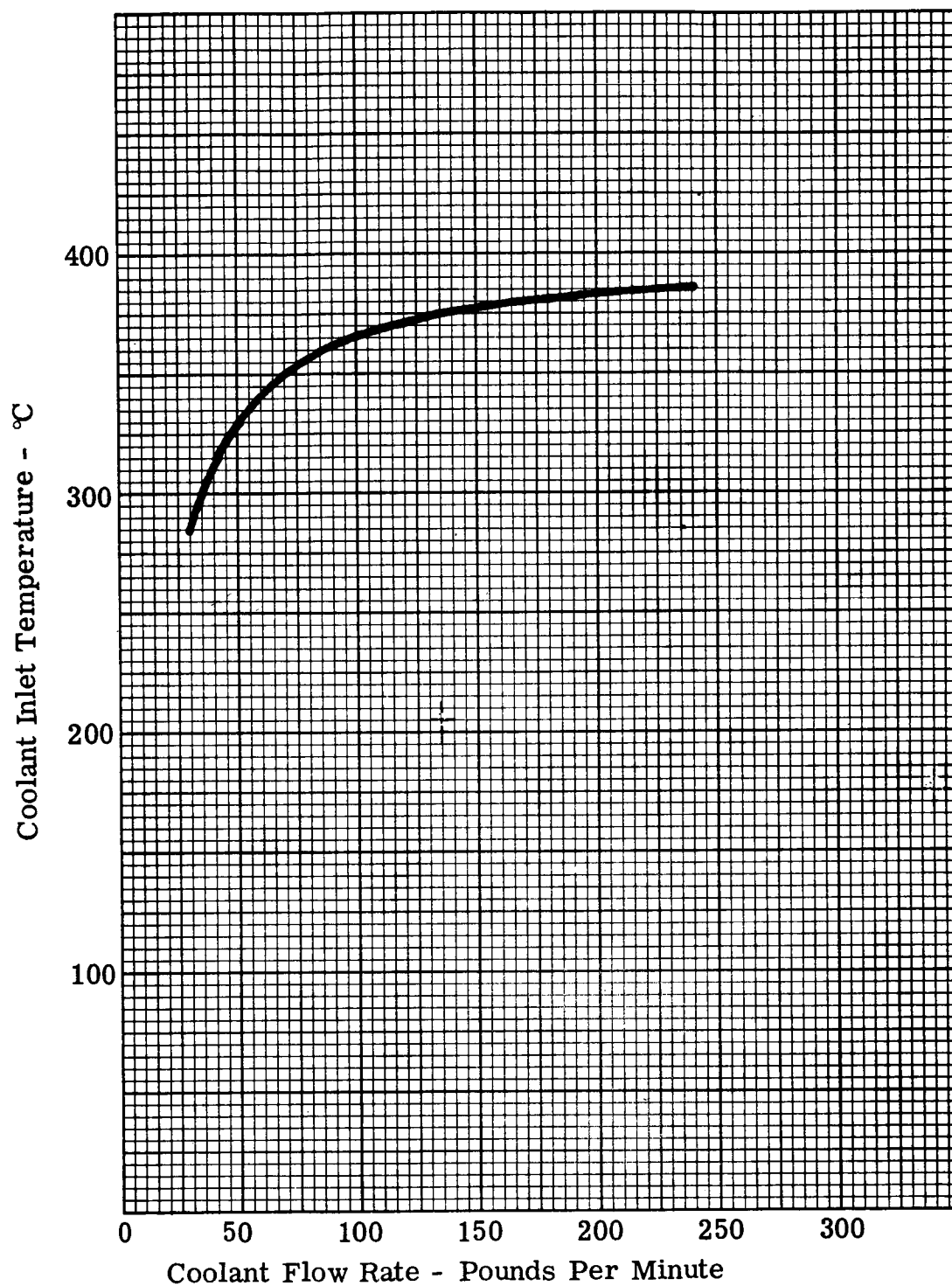


FIGURE 34

Transformer
One Megawatt, 400 CPS, 300 & 600 Volt Input
Coolant Inlet Temperature Vs. Coolant Flow Rate

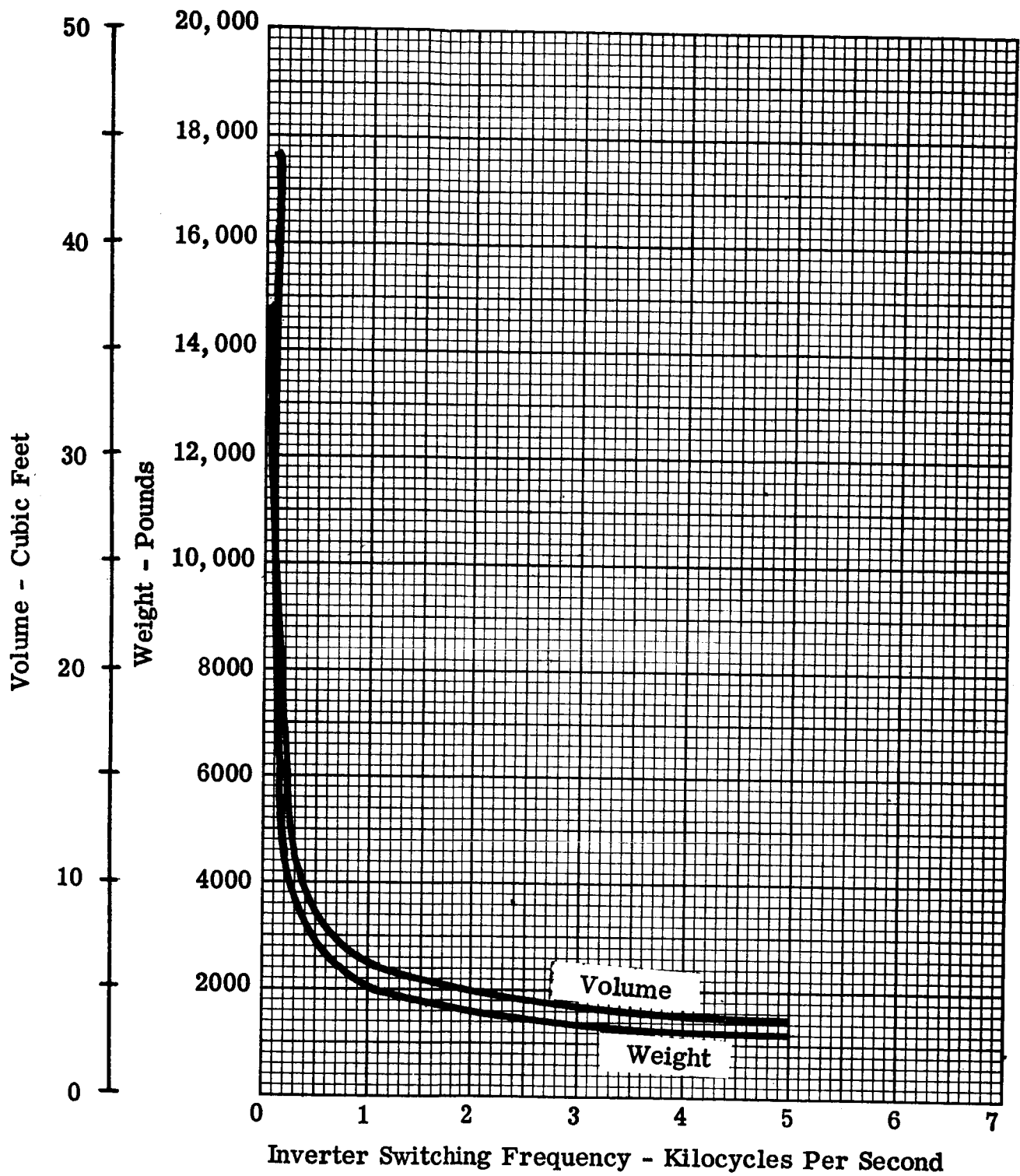


FIGURE 35
Transformer
One Megawatt, 300 & 600 Volts Input
Weight and Volume Vs. Inverter Switching Frequency

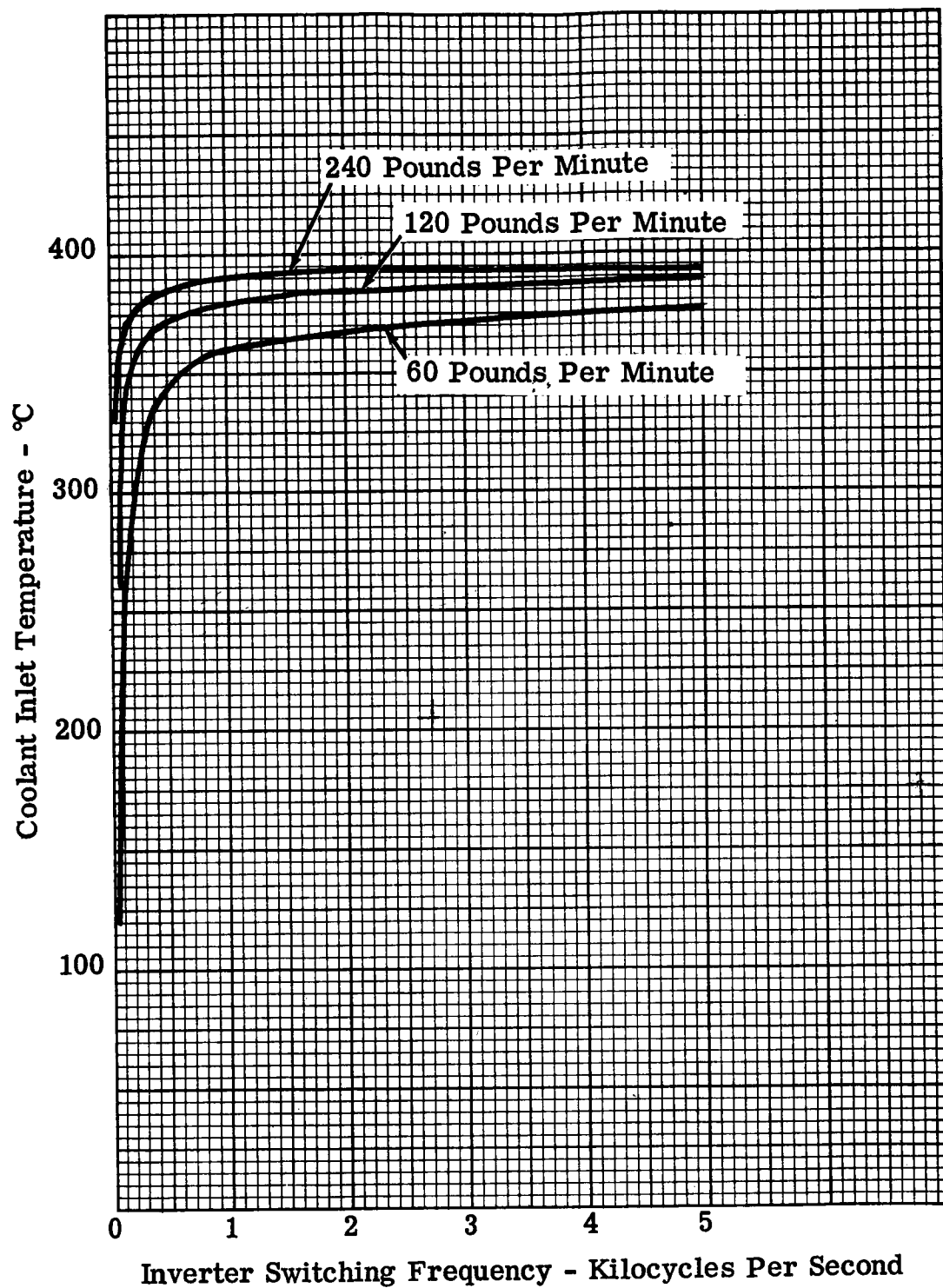


FIGURE 36

Transformer
One Megawatt, 300 & 600 Volt Input
Coolant Inlet Temperature Vs. Inverter Switching Frequency

Figures 34 to 36. Final choice of a design point, of course, must depend on consideration of all the electrical and mechanical parameters of the complete power system.

The effect of coolant flow rate on inlet temperature is given at 400 cycles per second, and variations of weight, volume, and coolant temperature with frequency are shown. From the curve of coolant inlet temperature versus flow rate, a coolant flow of about 60 pounds per minute is recommended. From frequency curves, transformer weight and volume are seen to rise sharply at frequencies below one kilocycle. A lower coolant inlet temperature is also required below one kilocycle, due to higher losses. Thus, frequencies of one kilocycle or higher are desirable.

D. POWER RECTIFIER

This part of the report presents the rectifier parametric data generated during this study. A brief description of the rectifier circuit, the electrical and mechanical design criteria, and the assumptions used to prepare the parametric data is presented. Also included in this section is consideration of the potential problem areas and recommendations for further study or investigation.

The rectifier systems studied are as follows:

<u>Systems</u>	<u>No. 1</u>	<u>No. 2</u>	<u>No. 3</u>	<u>No. 4</u>
D-C Output Power(kw)	500	1000	2000	5000
D-C Output Voltage(kv)	5	5	20	0.6 or 5
Rectifier Input Freq.(cps)	50-5000	50-5000	50-5000	50-5000
No. Bridge Rectifier Banks	1	1	1	8
Rectifier Bank Switch	no	no	no	yes

The parametric data for all of the above rectifier assemblies were prepared using silicon diodes as the rectifying elements. For comparative purposes parametric data was also prepared for a gas tube diode rectifier assembly for the one megawatt system, with input frequencies of 50 to 1,000 cycles per second.

Electrical Design

Operation and Circuit Description

The selection of single-phase rectification used in the determination of the parametric data was dictated by the choice of the single-phase inverter circuit. As described under the preliminary design, the bridge circuit is preferred and was selected for parametric study because it offers a power transformer of smaller size for the same d-c power delivered to the load.

Because the full-wave-bridge rectifier is a conventional circuit which is detailed in many electronic circuit textbooks, only a brief explanation of the basic circuit is presented. The bridge circuit, shown in Figure 37, consists of four legs. Each leg is made up of one or more diodes and the associated shunting elements. Each rectifier leg carries the total value of the direct current for 180 electrical degrees. Voltage division across the series diodes of the rectifier assemblies is accomplished by shunting

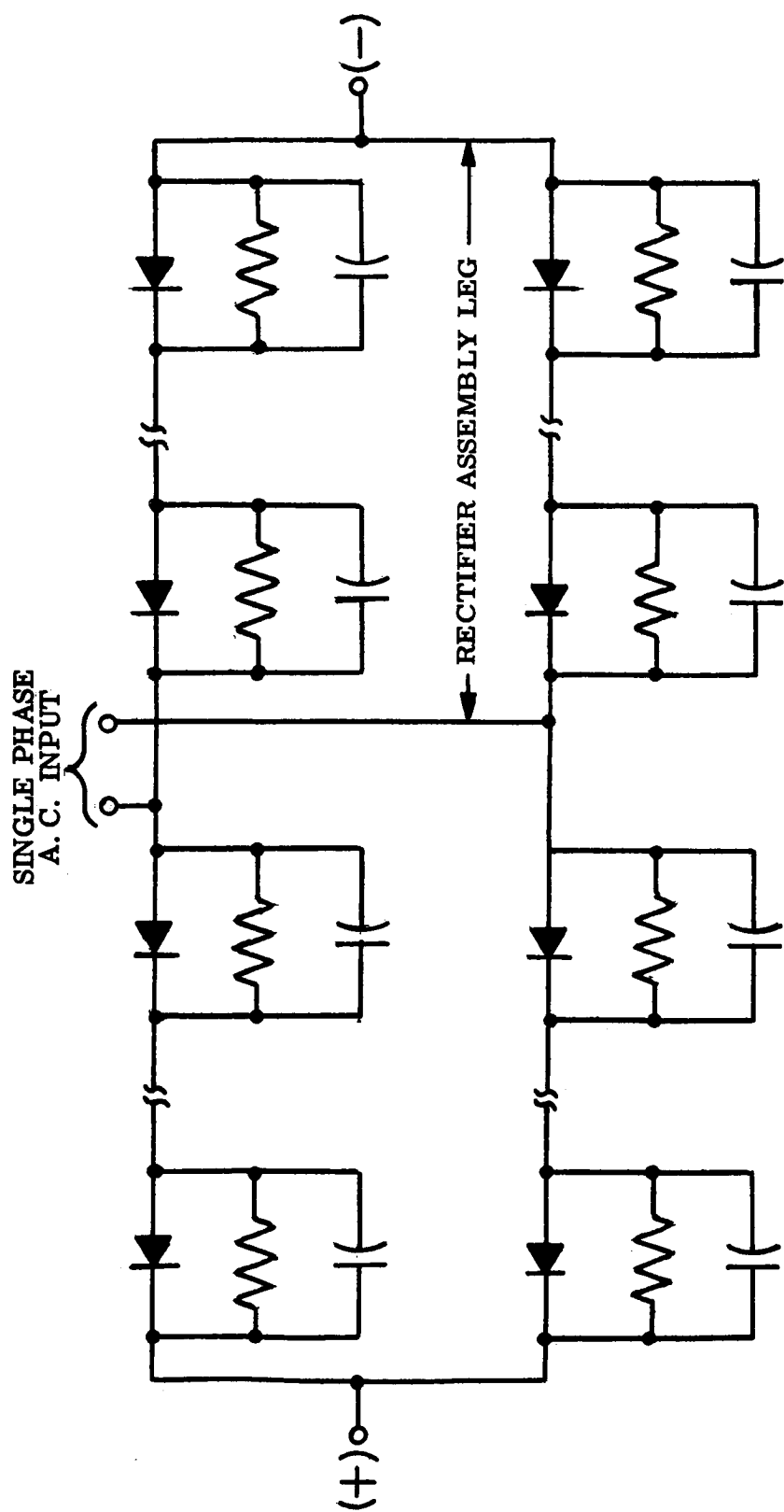


FIGURE 37
Schematic Single Phase Rectifier Bridge Assemblies

each silicon diode with a capacitor-resistor network. The value of the resistors combined with the reactance of the shunting capacitors provides a sufficiently low value of shunting impedance to insure uniform voltage division under steady state and transient voltage conditions.

Design Criteria

To calculate the parametric data, several design guide lines and basic assumptions are made as follows. The intent is to predict rectifier assemblies based on the characteristics of diodes available in 1968.

1. The number of diodes per rectifier bridge was determined by requiring that the diode peak inverse voltage (PIV) rating be at least 2.5 times the peak inverse voltage (PIV) seen by each diode under normal operation. This factor of 2.5, as explained in the earlier work of NAS5-1234, allows for voltage transients, unbalance between diodes and voltage balancing components, adequate derating for long life, and permits safe operation with some shorted diodes.
2. The current rating of the diodes is based on a minimum overload capacity of 400 percent for one second. This rating is more than adequate as determined from the electrical characteristics of the Pratt and Whitney Aircraft Megawatt Nuclear Reactor Thermionic Space Power Plant.
3. Diode manufacturers have indicated that semiconductor diode losses are essentially unaffected by operating frequencies up to 5000 cycles per second. This is particularly true of diffused junction diodes which, it is assumed, will be available in 1968 in the current and voltage rating selected for this study. Therefore, frequency is not considered in the computation of semiconductor rectifier losses. Semiconductor diode losses were calculated for reverse and forward current conduction only.

Frequency was considered in the diode losses of the gas-tube rectifier assembly in the computation of switching or commutating losses. Calculations were performed for the extreme frequencies of 50 and 1000 cycles per second. Because the diode commutating losses are a direct function of frequency and the diode operating peak voltage and current, the application of the gas-tube diode in a five-kilovolt system at frequencies above 1000 cycles per second is not considered feasible. The current rating of the gas tube diode selected for this application is 35 amperes RMS. The diode rating of 35 amperes, 15 kilovolts makes it possible to design a 1000 kilowatt, 5 kilovolt rectifier assembly with 10 parallel bridges. One diode per leg is used in each bridge. Paralleling the individual bridges is preferable to series operation since loss of one parallel bridge does

not incur the loss of the entire rectifier system. Semiconductor diode losses were calculated on the basis of using alloy junction diodes with a junction temperature of 277°F (142°C) which is a 25 percent derating from the supplier's specified maximum of 190°C. The gas-tube diodes were assumed to be capable of operating with heat rejection temperatures of 1112°F (600°C).

4. Silicon diodes are presently available in PIV ratings of 1000 volts at current ratings of 240 amperes half wave average. After consultation with diode manufacturers it was determined that normal improvements in the state of the art, by 1968, will permit diode ratings of 3000 PIV at 1000 amperes. See Table 21.

With exception of the 5 megawatt rectifier assembly which uses 1000 ampere, 2000 PIV silicon diodes, the systems used existing diode current ratings at 3000 volts PIV.

The gas tube diode used in the one megawatt high temperature rectifier assembly is capable of conducting 25 amperes average continuously at 15 kilovolts, although under normal operating conditions it is required to conduct 10 amperes average at approximately 5.7 kilovolts. The physical and electrical characteristics of the gas tube diode were obtained from NASA Lewis-Cleveland, Ohio, and the previous work performed on contract NAS5-1234.

5. With the exception of the five megawatt system which uses a resistor power dissipation derating of 16 percent, the minimum resistor power dissipation derating for the remaining rectifier assemblies is 42 percent when operating at normal system conditions at resistor body temperatures of 115°C.
6. The capacitor voltage rating is at least equal to the individual diode PIV rating at a capacitor body temperature of 115°C. This, therefore, is at least 2.5 times the peak working voltage seen by each capacitor under normal system operation. Capacitor losses have been calculated for the frequency extremes of 50 and 5000 cycles per second for all semiconductor rectifier systems and for the frequencies of 50 and 1000 cycles per second for the gas tube diode rectifier assembly.

Parametric Data

Tables 22 through 26 list the component quantities, size, weight, power losses, and conversion efficiency for the rectifier assemblies described previously. The curves of Figure 38 and 39 present the losses as a function of inverter frequency for the silicon diode and high temperature gas tube diode rectifier assemblies, respectively.

TABLE 21
PREDICTED CHARACTERISTICS OF
SILICON DIODES IN 1968

Characteristics will be similar to presently available diodes, except voltage ratings will be as high as 3000 volts.

In addition, very high power diodes will be available, with the following characteristics:

Predicted Characteristics of Silicon Diodes in 1968		Present Characteristics of Silicon Diodes
Rated Voltage (volts)	3000	1000
Rated Current (amperes)	1000 half wave	240
Junction Type	Diffused	Alloyed
Forward Drop	Similar to 1N3174A- Except 1000a, halfwave	See 1N3174A
Thermal Resistance	.05°C/watt	.20°C/watt
Max. Junction Temp.	200°C	190°C
Package Dimensions	3 in. x 3 in. base 4 in. height	Hex. 1¼ across flats 3.375
Terminals	Flag type	Flag type
Weight (lbs)	3	0.5
Mounting	Flat mounting surface, no stud	Flat surface with 3/4dia. stud.

TABLE 22

500 KILOWATT RECTIFIER - ONE BANK

SILICON DIODES

A-C Input Frequency (cps)	50	100	200	500	1000	2000	5000
D-C Bus Volts (kv)	5	5	5	5	5	5	5
Load D-C Amperes	100	100	100	100	100	100	100
<u>Diode</u>							
Amps/1Ø Bridge	100	100	100	100	100	100	100
Peak Amps	100	100	100	100	100	100	100
Avg. Amps	50	50	50	50	50	50	50
RMS Amps	70.7	70.7	70.7	70.7	70.7	70.7	70.7
Diode PIV	3000	3000	3000	3000	3000	3000	3000
Diodes/1Ø Bridge Leg	5	5	5	5	5	5	5
Diodes/1Ø Bridge	20	20	20	20	20	20	20
Diode Type	Similar to (W) Type 300 Except 3000 PIV						
Watts Loss/Diode	60.2	60.2	60.2	60.2	60.2	60.2	60.2
Total Diode Loss	1204	1204	1204	1204	1204	1204	1204
Total Diode Wt. (lbs)	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Total Diode Space Vol. (in ³)	52.4	52.4	52.4	52.4	52.4	52.4	52.4
<u>Resistor</u>							
Shunt Resistance (ohms)	125K	125K	125K	125K	125K	125K	125K
Watts Loss/Resistor	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Total Qty. Resistors	20	20	20	20	20	20	20
Total Resistor Watts	174	174	174	174	174	174	174
Total Resistor Wt. (lbs)	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Dimensions	2.78"L x 1.156"W Across Terminals & Mounting Lugs						
<u>Capacitor</u>							
Shunt Capacitor (mfd)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Watts Loss/Capacitor	0.09	0.182	0.377	1.06	2.65	7.1	30
Total Qty. Capacitors	20	20	20	20	20	20	20
Total Capacitor Watts	1.8	3.64	7.54	21.2	53.0	142.0	600
Total Capacitor Wt. (lbs)	9	9	9	9	9	9	9
Dimensions	2.04"L x .54"W x 1.375"H Terminal Height .812"						
Total Assembly Losses (watts)	1379.8	1381.6	1385.5	1399.2	1431	1520	1978
Rectifier Conversion Efficiency (percent)	99.72	99.72	99.72	99.72	99.71	99.70	99.60
Total Component Assembly Wt. (lbs)	15.7	15.7	15.7	15.7	15.7	15.7	15.7

TABLE 23

ONE MEGAWATT RECTIFIER - ONE BANK

SILICON DIODES

A-C Input Frequency (cps)	50	100	200	500	1000	2000	5000
D-C Bus Volts (kv)	5	5	5	5	5	5	5
Load D-C Amperes	200	200	200	200	200	200	200
<u>Diode</u>							
Amps/1Ø Bridge	200	200	200	200	200	200	200
Peak Amps	200	200	200	200	200	200	200
Avg. Amps	100	100	100	100	100	100	100
RMS Amps	141	141	141	141	141	141	141
Diode PIV	3000	3000	3000	3000	3000	3000	3000
Diodes/1Ø Bridge Leg	5	5	5	5	5	5	5
Diodes/1Ø Bridge	20	20	20	20	20	20	20
Diode Type	Similar to JEDEC 1N3174A Except						3000 PIV
Watts Loss/Diode	120	120	120	120	120	120	120
Total Diode Loss	2400	2400	2400	2400	2400	2400	2400
Total Diode Wt. (lbs)	15.7	15.7	15.7	15.7	15.7	15.7	15.7
Total Diode Space Vol. (in ³)	142	142	142	142	142	142	142
<u>Resistor</u>							
Shunt Resistance (ohms)	70K	70K	70K	70K	70K	70K	70K
Watts Loss/Resistor	9	9	9	9	9	9	9
Total Qty. Resistors	40	40	40	40	40	40	40
Total Resistors Watts	360	360	360	360	360	360	360
Total Resistor Wt. (lbs)	2.2	2.2	2.2	2.2	2.2	2.2	2.2
<u>Capacitor</u>							
Shunt Capacitor (mfd)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Watts Loss/Capacitor	0.09	0.182	0.377	1.06	2.65	7.1	30
Total Qty. Capacitors	20	20	20	20	20	20	20
Total Capacitor Watts	1.8	3.64	7.54	21.2	53.0	142.0	600
Total Capacitor Wt. (lbs)	9	9	9	9	9	9	9
Total Assembly Losses (watts)	2761.8	2763.6	2767.5	2781.2	2813	2902	3360
Rectifier Conversion Efficiency (percent)	99.72	99.72	99.72	99.72	99.72	99.71	99.66
Total Component Assembly Weight (lbs)	26.9	26.9	26.9	26.9	26.9	26.9	26.9

TABLE 24

TWO MEGAWATT RECTIFIER - ONE BANK

SILICON DIODES

A-C Input Frequency (cps)	50	100	200	500	1000	2000	5000
D-C Bus Volts (kv)	20	20	20	20	20	20	20
Load D-C Amps	100	100	100	100	100	100	100
<u>Diode</u>							
Amps/1Ø Bridge	100	100	100	100	100	100	100
Peak Amps	100	100	100	100	100	100	100
Avg. Amps	50	50	50	50	50	50	50
RMS Amps	70.7	70.7	70.7	70.7	70.7	70.7	70.7
Diode PIV	3000	3000	3000	3000	3000	3000	3000
Diode/1Ø Bridge Leg	19	19	19	19	19	19	19
Diode/1Ø Bridge	76	76	76	76	76	76	76
Diode Type	Similar to (W) Type 300 Except 3000 PIV						
Watts Loss/Diode	61.2	61.2	61.2	61.2	61.2	61.2	61.2
Total Diode Loss	4651	4651	4651	4651	4651	4651	4651
Total Diode Wt. (lbs)	21.4	21.4	21.4	21.4	21.4	21.4	21.4
Total Diode Space Vol. (in3)	199	199	199	199	199	199	199
<u>Resistor</u>							
Shunt Resistance (ohms)	125K	125K	125K	125K	125K	125K	125K
Watts Loss/Resistor	9.6	9.6	9.6	9.6	9.6	9.6	9.6
Total Qty. Resistors	76	76	76	76	76	76	76
Total Resistor Watts	730	730	730	730	730	730	730
Total Resistor Wt. (lbs)	4.1	4.1	4.1	4.1	4.1	4.1	4.1
Dimensions	2.78"L x 1.156"W Across Terminals & Mounting Lugs						
<u>Capacitor</u>							
Shunt Capacitor (mfd)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Watts Loss/Capacitor	0.09	0.182	0.377	1.06	2.65	7.1	30
Total Qty. Capacitors	76	76	76	76	76	76	76
Total Capacitor Watts	6.84	13.8	28.6	80.5	209	540	2280
Total Capacitor Wt. (lbs)	34.6	34.6	34.6	34.6	34.6	34.6	34.6
Dimensions	2.04"L x .54"W x 1.375"H Terminal Height .812"						
Total Assembly Losses (watts)							
	5387.8	5394.8	5409.6	5461.5	5590	5921	7661
Rectifier Conversion Efficiency (percent)							
	99.73	99.73	99.73	99.73	99.72	99.70	99.61
Total Component Assembly Weight (lbs)							
	60.1	60.1	60.1	60.1	60.1	60.1	60.1

TABLE 25
FIVE MEGAWATT RECTIFIER - 8 BANKS

SILICON DIODES

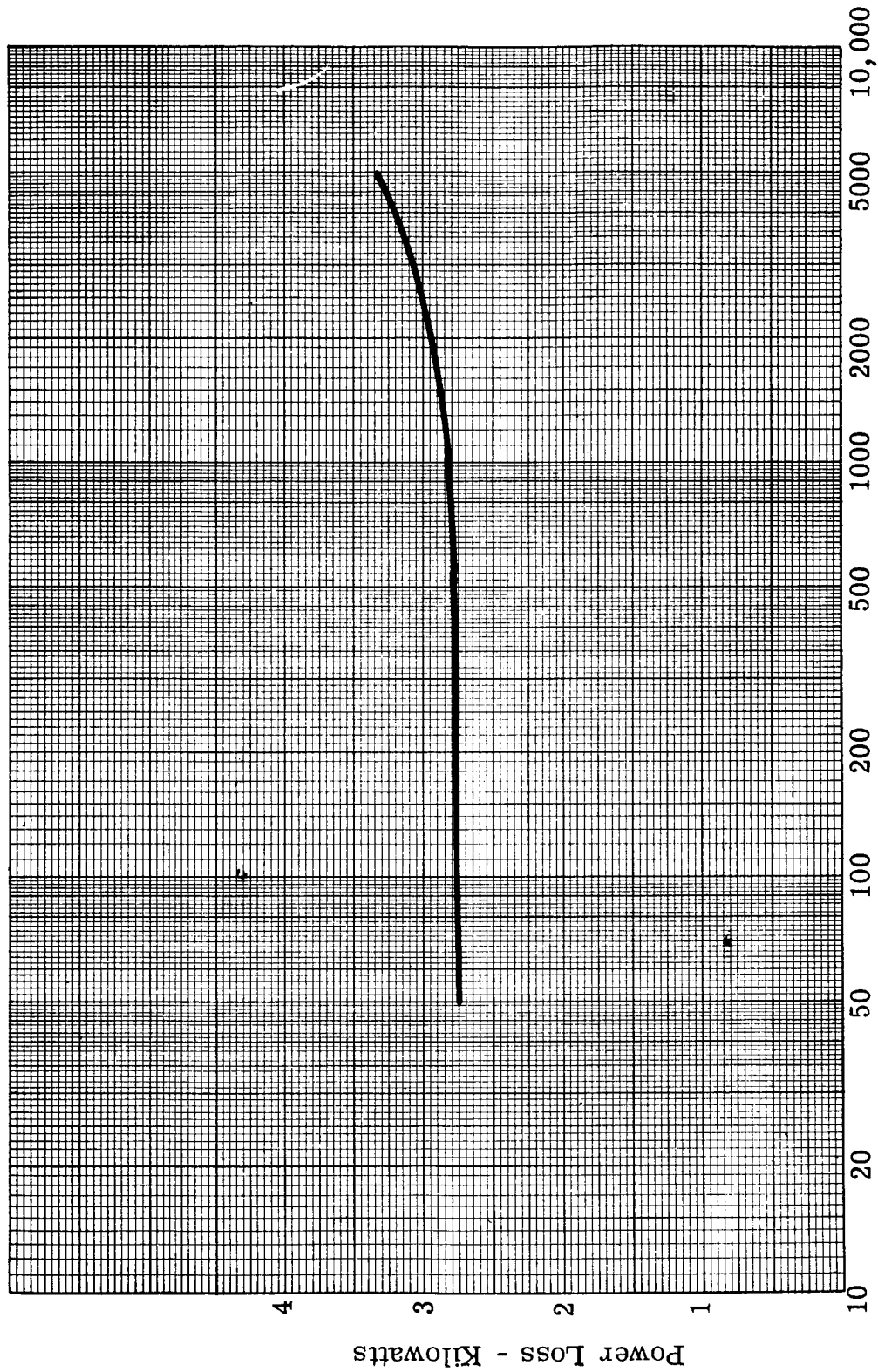
D-C Bus Volts (kv) Rect. Bank Condition A-C Input Freq. (cps) Load D-C Amps	0.6 8 Parallel										5 8 Series				
	50	100	200	500	1000	2000	5000	50	100	200	500	1000	2000	5000	1,000
1,042	1,042	1,042	1,042	1,042	1,042	1,042	1,042	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
1,042	1,042	1,042	1,042	1,042	1,042	1,042	1,042	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
521	521	521	521	521	521	521	521	500	500	500	500	500	500	500	500
737	737	737	737	737	737	737	737	707	707	707	707	707	707	707	707
2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
625	625	625	625	625	625	625	625	600	600	600	600	600	600	600	600
20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	19,200	19,200	19,200	19,200	19,200	19,200	19,200	19,200
723	723	723	723	723	723	723	723	723	723	723	723	723	723	723	723
Resistor Shunt Resistance (ohms) Watts Loss/Resistor Total Qty. Resistors Total Resistor Watts Total Resistor Wt (lbs) Dimensions	15K	15K	15K	15K	15K	15K	15K	15K	15K	15K	15K	15K	15K	15K	15K
	13	13	13	13	13	13	13	14	14	14	14	14	14	14	14
Capacitor Shunt Capacitor (mfd) Watts Loss/Capacitor Total Qty. Capacitors Total Capacitor Watts Total Capacitor Wt. (lbs) Dimensions	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
	832	832	832	832	832	832	832	896	896	896	896	896	896	896	896
Total Assy. Losses (watts) Rectifier Conv. Eff. (%) Total Component Assy. Wt. (lbs)	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5
	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs	2.78"L x 1.156"W Across Terminal & Mounting Lugs
Total Assy. Losses (watts) Rectifier Conv. Eff. (%) Total Component Assy. Wt. (lbs)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	0.08	0.164	0.338	0.95	2.4	6.34	28.1	0.09	0.177	0.366	1.04	2.58	6.87	30.5	64
Total Assy. Losses (watts) Rectifier Conv. Eff. (%) Total Component Assy. Wt. (lbs)	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64
	5.1	10.5	21.6	60.6	153	405	1800	5.8	11.3	23.4	66.5	165	440	1952	37
Total Assy. Losses (watts) Rectifier Conv. Eff. (%) Total Component Assy. Wt. (lbs)	37	37	37	37	37	37	37	37	37	37	37	37	37	37	37
	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"	2.04"L x .54"W x 1.75"H Terminal Height .812"
Total Assy. Losses (watts) Rectifier Conv. Eff. (%) Total Component Assy. Wt. (lbs)	20,837	20,843	20,854	20,893	20,985	21,237	22,632	20,102	20,107	20,119	20,163	20,261	20,536	22,046	99.60
	99.58	99.58	99.58	99.58	99.58	99.58	99.54	99.60	99.60	99.60	99.60	99.59	99.59	99.56	167.5
Total Assy. Losses (watts) Rectifier Conv. Eff. (%) Total Component Assy. Wt. (lbs)	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5
	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5

TABLE 26

1,000 KILOWATT RECTIFIER-10 PARALLEL BANKS

GAS TUBE DIODES

A-C Input Frequency (cps)	50	100	200	500	1000
D-C Bus Volts (kv)	5	5	5	5	5
Load D-C Amps	200	200	200	200	200
<u>Diode</u>					
Amps/1Ø Bridge	20	20	20	20	20
Peak Amps	20	20	20	20	20
Avg. Amps	10	10	10	10	10
RMS Amps	14.1	14.1	14.1	14.1	14.1
Diode PIV (kv)	15	15	15	15	15
Diode/1Ø Bridge Leg	1	1	1	1	1
Diode/1Ø Bridge	4	4	4	4	4
Total Qty. Diodes	40	40	40	40	40
Diode Rating	35 Amps RMS, 15 kv				
Watts Loss/Diode	125	175	275	575	1075
Total Diode Loss	5000	7000	11,000	23,000	43,000
Total Diode Wt. (lbs)	40	40	40	40	40
Total Diode Space Vol. (in ³)	1000	1000	1000	1000	1000
Total Assembly Losses (watts)	5000	7000	11000	23000	43000
Rectifier Conversion Efficiency (percent)	99.50	99.30	98.91	97.75	95.87
Total Component Assembly Weight (lbs)	40	40	40	40	40



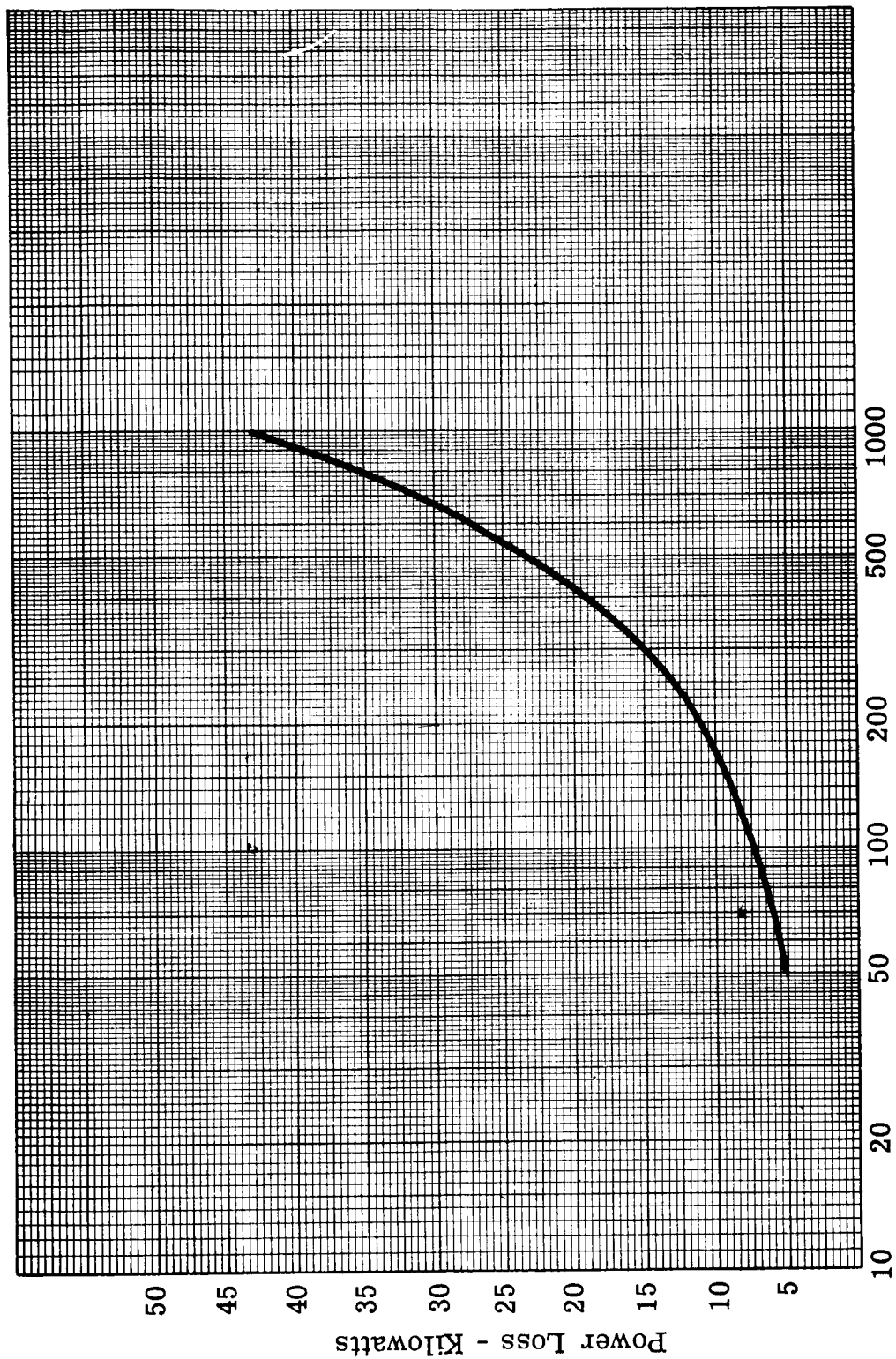
Inverter Switching Frequency - Cycles Per Second

FIGURE 38

Rectifier Assembly
Silicon Diode

One Megawatt

Power Losses Vs. Inverter Switching Frequency



Inverter Switching Frequency - Cycles Per Second

FIGURE 39

Rectifier Assembly

Gas Tube Diode

One Megawatt

Power Losses Vs. Inverter Switching Frequency

Because the rectifier bridge currents for the 500-and 2,000-kilowatt silicon-diode rectifier systems are equal, the diodes for each of these systems are identical. Also, because the voltage safety factor for all of the rectifier assemblies is not less than 2.5, the ohmic value of the voltage equalizing resistors for these two power outputs is the same. Tabulated data for these two systems are shown in Table 22 and 24, respectively. The diodes selected for the 1,000-and 5,000-kw rectifier systems are different from each other and from the 500-and 2,000-kw systems because of the different rectifier bridge output currents. The tabulated data for the 1,000 and 5,000-kw silicon diode rectifier systems are presented in Tables 23 and 25, respectively.

Problem Areas

The application of practical rectifier assemblies in d-c to d-c converters requires an investigation into the characteristics which can influence system operation.

1. Radio Interference

Rectifier equipment is a source of radio noise which is generated by the diodes in their normal commutation of load current. The presence of radio frequency currents and voltages in the d-c output circuit may cause interference in communication circuits exposed to the load circuit. The radio-frequency harmonics in the d-c output can be reduced to ineffective values by means of a series reactor and shunt element such as a capacitor or several combinations of resonant reactor-capacitors.

2. Voltage Transients

Voltage transients as high as eight times the normal peak reverse voltage may be reflected across the silicon rectifiers when the primary circuit of a transformer-rectifier is opened. This transient voltage is created when the transformer magnetizing current and flux collapse suddenly coupling high voltage into the transformer secondary. The voltage transients may be reduced by the use of diodes with two or three times the normal peak reverse voltage of the system combined with capacitor suppressor circuits.

Another potential problem area is foreseen with the use of gas-tube diodes as the rectifying elements. These tubes require a separate filament power-source of approximately 25 watts for each tube when heat-rejection temperature is at 600°C. It is assumed that the filament power source is d-c taken directly from the nuclear-thermionic generator. The tube filament voltage requirements, which will probably be less than 5 volts, must be regulated within $\pm 5\%$ to maintain satisfactory tube operation and life. Therefore, should a

high temperature gas tube rectifier assembly appear feasible it would be necessary to develop a high temperature low voltage regulator.

Analysis and Recommendations

As seen from Tables 22 through 25, the silicon semiconductor rectifier assemblies offer conversion efficiencies in excess of 99 percent for all of the d-c power outputs studied. With the exception of the 1000-ampere diode used in the five-megawatt assemblies, diodes having the proper current ratings for the remaining rectifier assemblies are available in production quantities. It is assumed that normal advancement in the state of the art, as dictated by economics, will see the increase of silicon semiconductor voltage ratings to 3000 PIV by 1968. This voltage rating was used in preparing the parametric data for this study. Even with the use of 3000-PIV diodes, 19 series diodes per rectifier leg were used for the two megawatt, 20 kilovolt assembly. Should the semiconductor rectifiers prove feasible, in this application, it is recommended that the PIV diode rating be increased above 3000 volts to reduce the quantity of series diodes and the associated shunt resistor-capacitor components.

To accomplish voltage division across each of the series diodes of the semiconductor rectifier assemblies the shunt resistor-capacitor combination is used as explained earlier.

From Table 26 it is seen that the use of 600°C gas-tube diode rectifier assemblies causes a power loss of approximately 1100 watts per diode and 43,000 watts total in a one megawatt-, five-kilovolt system when operating with a rectifier input frequency of 1000 cycles per second. Should these rectifying elements appear feasible, for this application, it is recommended that study and development be expended to significantly reduce the assumed total commutating time of 60 microseconds. Reduction of the diode conducting rise and fall time will reduce the power losses at 1000 cycles per second and perhaps permit satisfactory operation at a frequency of 2000 cycles per second, which would aid in reducing transformer and output filter size and weight.

Because the use of gas-tube diodes will require filament voltage regulation, probably within $\pm 5\%$, it is further recommended that a study and development feasibility of a low-voltage-, high-temperature regulator tube be undertaken in conjunction with the gas tube diode development.

Mechanical Design

Description

In silicon-diode rectifier systems, the mechanical design is based on the use of cold-plate cooling with liquid-metal coolant. In 500-, 1000-, and 2000-kilowatt systems, diodes are stud-mounted to beryllium oxide insulation blocks. In the 500-kilowatt systems, in which each diode must dissipate 625 watts, diodes are adhesive bonded to the insulation. In all cases, the insulation is bonded to the cold plate. Adhesive bonding is used to reduce the thermal resistance across the joints in a space environment.

Capacitors and resistors used in conjunction with the diodes are contained in insulated cases, and are mounted directly to the cold plate, adjacent to the diodes.

Beryllium oxide insulation is used both to provide required dielectric strength and to provide a good thermal path to conduct heat from the diodes to the cold plate. Thus, in all but the 20-kilovolt design, the insulation thickness is dictated by thermal conduction requirements rather than dielectric requirements. Using single blocks for each diode instead of an integral plate provides relief from thermal stresses in adhesive bonding as well as low weight.

Coolant tubes and cold plate are of beryllium to achieve low weight with the required resistance to corrosion by liquid metal. The coolant is eutectic NaK. Diodes are mounted in rows to the cold plate. Each row is cooled by four coolant ducts parallel to the row. Details of the diode arrangement are given in Table 27.

TABLE 27

RECTIFIER DIODE ARRANGEMENT

System Rating (kw)	500	100	2000	5000
No. of Diodes	20	20	76	32
Diodes per Row	5	5	9 & 10	4
Rows per Deck	2	2	4	4
No. per Deck	2	2	2	2

The mechanical design of the high temperature gas tube rectifiers is based on cold plate cooling. The gas tube diodes are mounted to a cold plate which has integral coolant ducts routed adjacent to them. Electrical leads from the diodes serve as mounting flanges and provide heat conduction paths. Beryllium oxide is used to insulate the leads from the cold plate. The diodes are cooled directly by conduction from the flanges through insulation to the cold plate. The electric conducting flanges are adhesive bonded to the insulation, which in turn is bonded to the cold plate, to reduce thermal resistance across the joints and are mechanically fastened to insure structural reliability. Cold plate and cooling tubes are of titanium.

Design Criteria

The following basic design criteria are used to calculate the required parametric data.

1. The coolant was assumed to be eutectic NaK, which has a specific heat of $0.210 \text{ Btu/lb-}^{\circ}\text{F}$, and a density of 0.0306 lbs/in^3 . Convection temperature drop is 1°C .
2. Beryllium oxide insulation has the following characteristics:

Dielectric Strength	300 volts/mil
Density	0.015 lbs.in^3
Thermal Conductivity	$100 \text{ Btu/hr-ft-}^{\circ}\text{F}$ at 1000°C
Thermal Expansion	$3.2 \times 10^{-6} \text{ in/in/}^{\circ}\text{F}$ from 0 to 200°C $5.0 \times 10^{-6} \text{ in/in/}^{\circ}\text{F}$ from 400 to 600°C

3. Beryllium for use in coolant tubes and cold plate has the following characteristics:

Density	0.067 lbs/in^3
Thermal Conductivity	$87 \text{ Btu/hr-ft-}^{\circ}\text{F}$
Thermal Expansion	$6.4 \times 10^{-6} \text{ in/in/}^{\circ}\text{F}$

4. Columbium for use in coolant tubes and coolant jacket, cold plate and flanges has the following characteristics:

Density	0.310 lbs/in ³
Thermal Conductivity	31.5 Btu/hr-ft-°F
Thermal Expansion	3.82 x 10 ⁻⁶ in/in-°F
5. Titanium for use in coolant tubes and cold plate has the following characteristics:

Density	0.163 lbs/in ³
Thermal Conductivity	4.3 Btu/hr-ft-°F
Thermal Expansion	5.8 x 10 ⁻⁶ in/in/°F
6. Adhesive bonding is .002 inch thick, with a thermal conductivity of 0.227 Btu/hr-ft-°F.
7. Minimum achievable thermal resistance between two surfaces not bonded together is 0.2°C/watt in a space environment.
8. Semiconductor diode stud or case temperature is 115°C for all designs. This is approximately equivalent to 25 percent derating of the diode junction temperature.
9. Gas tube diode electrical connections, which serve as mount flanges, are held to 600°C.
10. Supporting structure weight, not included in the weight of cold plate, insulation, and coolant tube, is 20 percent of the total weight.

Parametric Data

Parameters for silicon-diode systems are given in Figures 40, 41, and 42. Weights and volumes are given in Table 28. Figure 40 shows rectifier system total weight as a function of power rating. For comparative purposes, curves are given for systems utilizing beryllium, titanium, and columbium in the coolant tubes and cold plate. Figure 41 gives package volume as a function of power rating. Weight and volume are constant at all frequencies. Figure 42 presents required fluid inlet temperature as a function of coolant flow for each power rating for rectifier assembly input frequency of 50 and 5000 cps.

Comparative weights and volumes for the silicon diode and gas tube rectifier systems are shown in Table 29 for a one-megawatt rating.

TABLE 29

ONE-MEGAWATT RECTIFICATION SYSTEMS

Parameter	Silicon Diode System	Gas Tube Diode System
Total Weight (lbs)	58.3	122
Total Volume (cu.ft.)	1.93	4.9

Figure 43 presents required coolant inlet temperatures for the gas tube rectifier systems as a function of coolant flow at rectifier assembly input frequencies of 50 and 1000 cps.

Problem Areas

1. A major problem area which will require development effort is in the use of beryllium for coolant tubes and cold plate. Reliable techniques for forming and joining beryllium must be developed, as well as for joining beryllium to other metals which might be used in a complete power system cooling loop. If the use of beryllium should prove infeasible in 1968, another material such as titanium or columbium would have to be used. Figure 40 is presented to show the weight penalty incurred by use of these materials.
2. Development of reliable adhesive bonds is required for use in a space environment. It should be either sufficiently elastic to relieve thermal expansion differentials, or

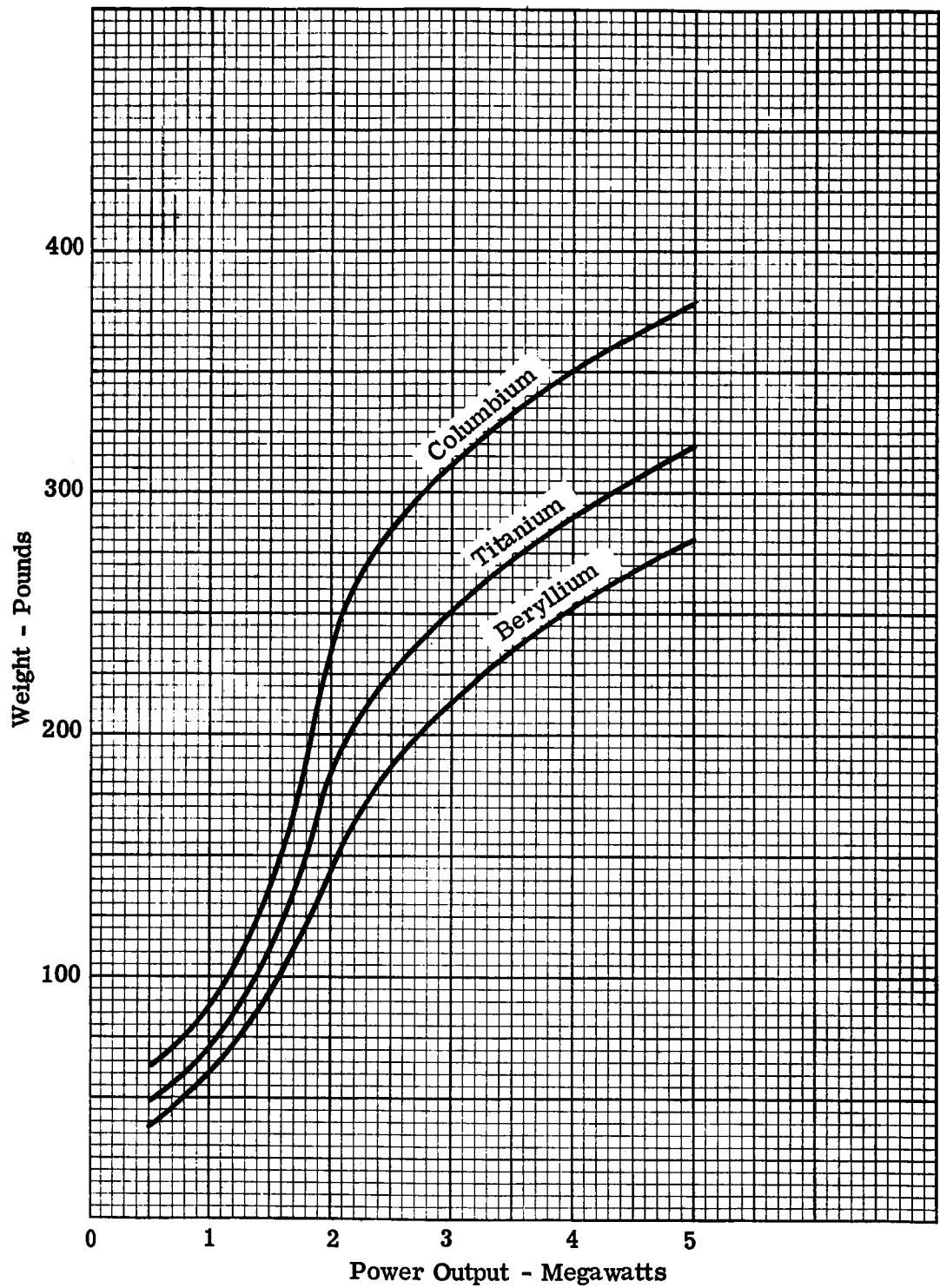


FIGURE 40
Rectifier
Silicon Diode Assemblies
Weight Vs. Power Output

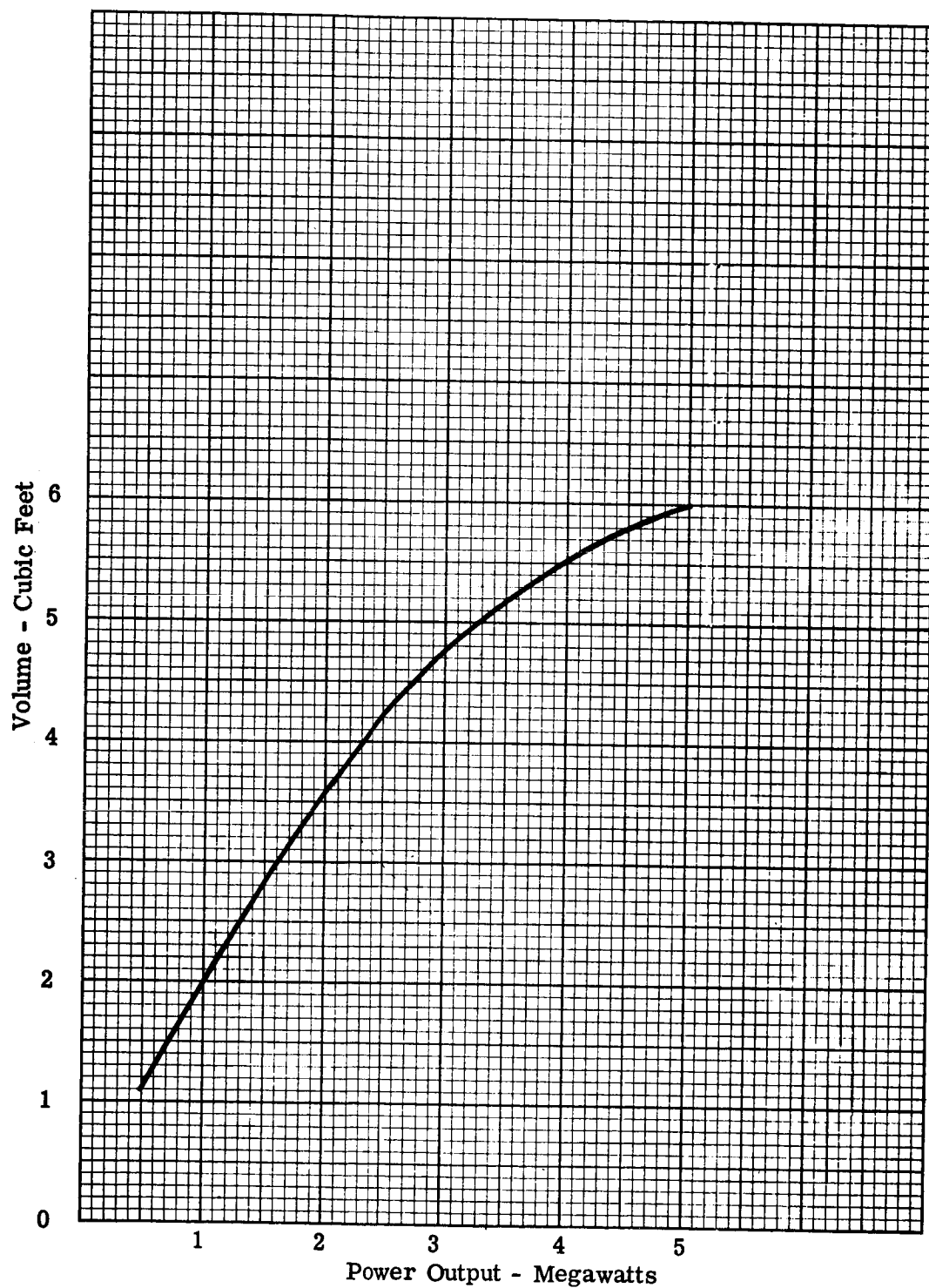


FIGURE 41

Rectifier
Silicon Diode Assemblies
Volume Vs. Power Output

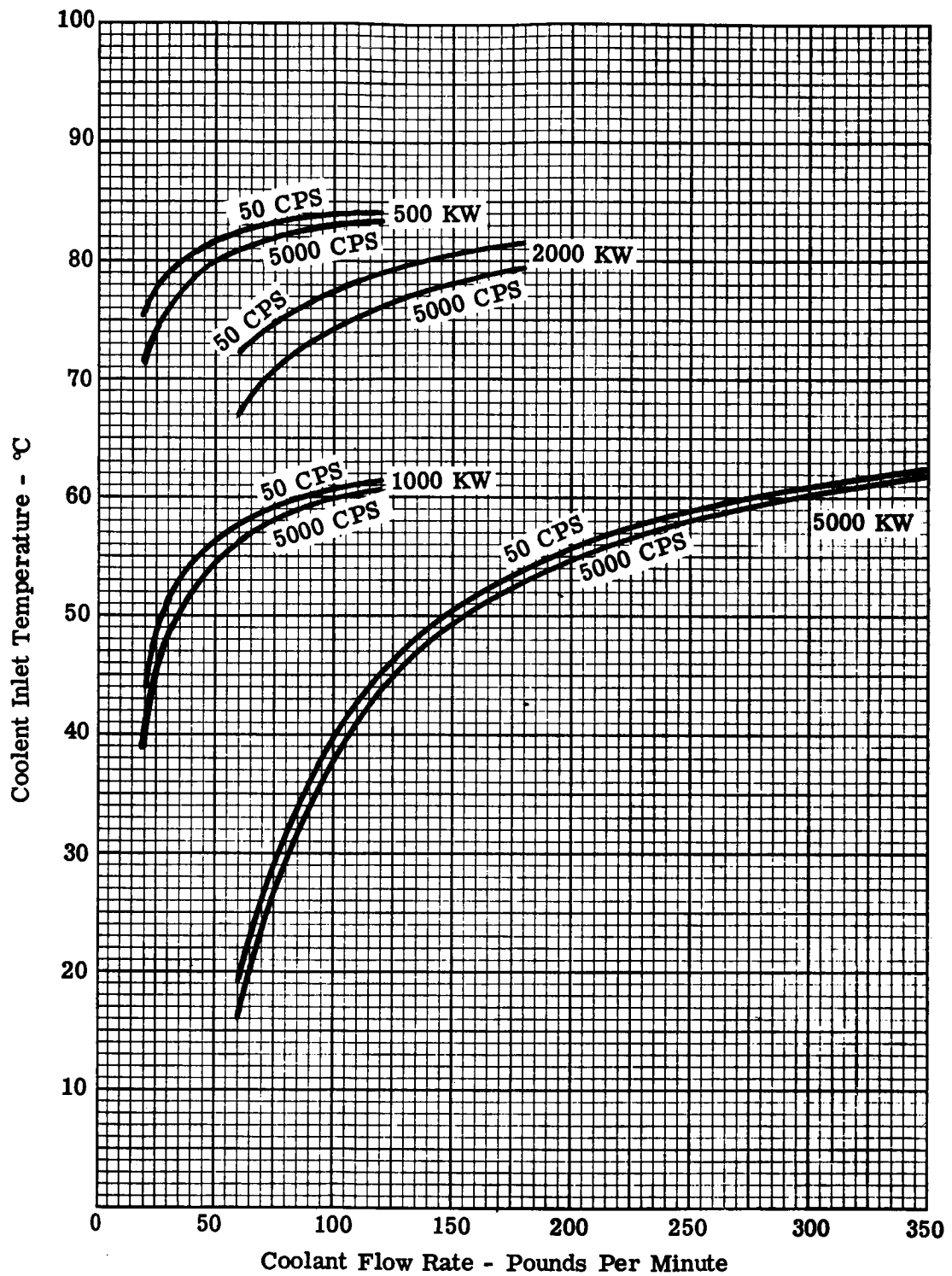


FIGURE 42.

Rectifier
Silicon Diode Assemblies
Coolant Inlet Temperature Vs. Coolant Flow Rate

TABLE 28

SILICON DIODE RECTIFICATION SYSTEMS

WEIGHT AND VOLUMES

	Beryllium Design				Titanium Design				Columbium Design			
	0.5	1.0	2.0	5.0	0.5	1.0	2.0	5.0	0.5	1.0	2.0	5.0
Power (megawatts)	37.6	58.3	143.5	281	47.3	68.5	180.2	320	62.2	84.5	236.5	380
Total Weight (lbs)	1.07	1.93	3.61	6.0	1.07	1.93	3.61	6.0	1.07	1.93	3.61	6.0
Total Volume (cu.ft.)	0.075	0.058	0.071	0.056	0.094	0.068	0.090	0.064	0.124	0.084	0.118	0.076
Specific Weight (lbs/kw)												

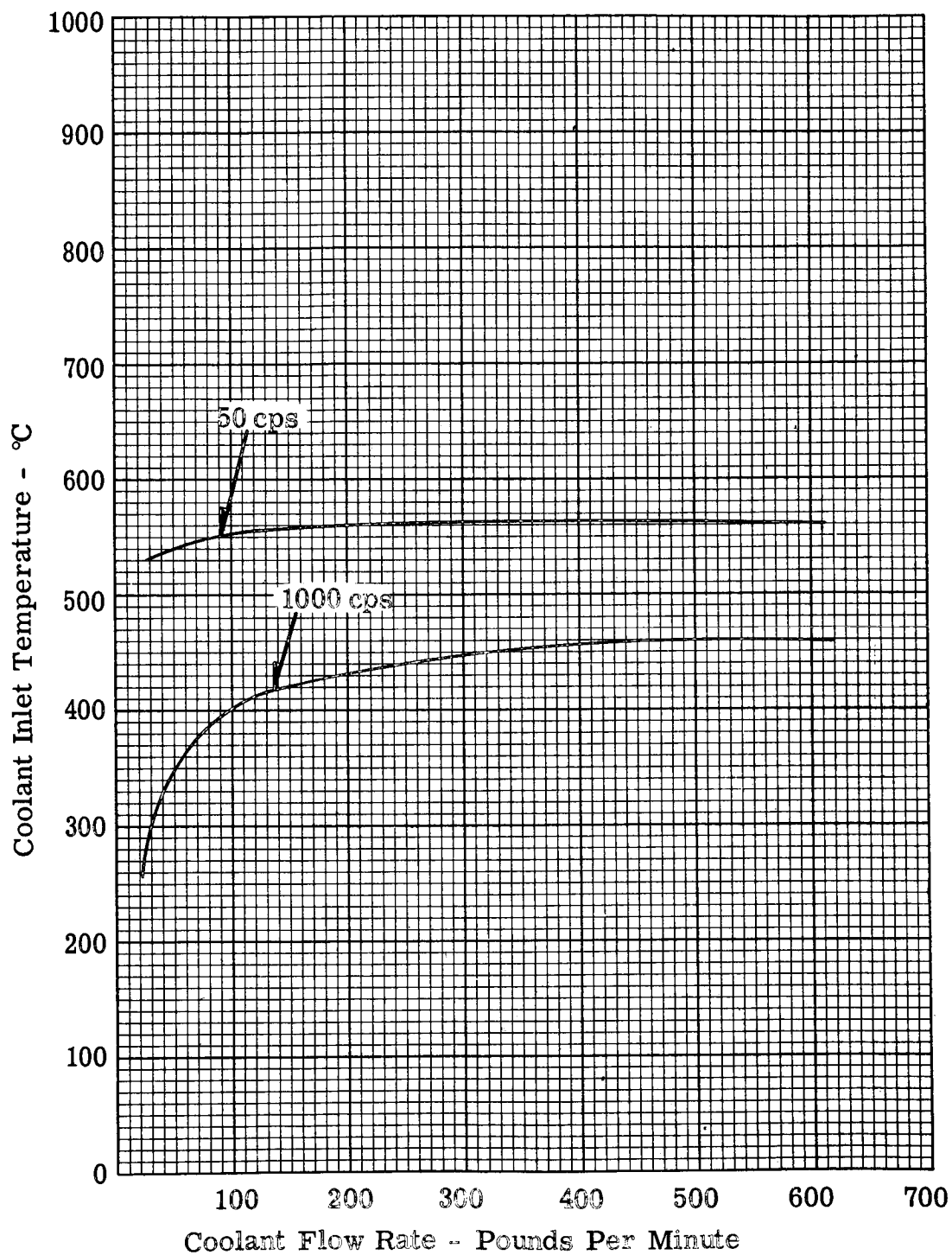


FIGURE 43

Rectifiers

Gas Tube Diode Assemblies

Coolant Inlet Temperature Vs. Coolant Flow Rate

strong enough to resist thermal stresses created between materials of different relative expansions.

Analysis and Recommendations

From Table 28, the one-and five-megawatt designs give the lowest specific weights, and therefore appear desirable. However, the parametric data presented for mechanical characteristics of silicon-diode rectifier assemblies are not sufficient in themselves to warrant recommendation of any particular power rating. These data would have to be considered in conjunction with electrical and mechanical parameters of a complete power system to choose an optimum design point.

Allowable coolant inlet temperature is noted to be substantially higher for the 500-and 2000-kw assemblies than for the one-and five-megawatt assemblies. This results from the 500-and 2000-kilowatt assemblies having individual diode losses about half those for the one-megawatt assembly and one-tenth those for the five-megawatt assembly. Lower individual diode losses allow a lower conduction temperature drop from the diode to the coolant conduit wall, with a resulting higher allowed coolant temperature.

In the five-megawatt assembly, coolant temperature is held in the same range as the one-megawatt assembly, despite individual diode losses about five times as high. This is achieved by use of a larger diode dissipating surface area, use of adhesive bond between the diode and the insulation, and use of higher coolant flow rate as indicated in the curve.

Gas-tube rectifier assemblies are substantially larger and heavier than silicon-diode assemblies as indicated in Table 28 and also yield higher total losses, as indicated in Tables 23 and 26. Thus, silicon-diode rectification appears most desirable.

For low frequencies, however, about 50 cycles per second, the allowable coolant inlet temperature is about 400°C to 500°C higher than that for silicon diodes. Such an increase in allowable coolant temperature might offset the drawbacks of larger size, weight, and losses noted above. This should be determined from consideration of the rectifier as a part of the entire power system.

In summary, the use of silicon-diode rectification is recommended unless the high allowable coolant temperature of a gas tube assembly offsets its disadvantages of high weight, large volume, and high losses.

Should a gas tube rectifier assembly be desirable, a development program should be implemented to solve the problems inherent in cooling the diodes and determine the feasibility of this approach.

The use of beryllium for coolant tubes and cold plate is strongly recommended at coolant temperatures below 200°C to achieve a lower weight system. A program should be implemented to develop reliable forming and joining techniques for beryllium, if such a system is to be feasible in 1968.

E. OUTPUT FILTER

This presents the output filter parametric data generated during this study. A brief description of the filter circuit, the electrical and mechanical design criteria, and the assumptions used to prepare the parametric data is presented. Also included in this section is consideration of the potential problem areas and recommendations for further study or investigation.

The output filters are presented for the following d-c to d-c converter systems.

	No. 1	No. 2	No. 3	No. 4
D-C Output Power, kw	500	1000	2000	5000
D-C Output Voltage, kv	5	5	20	0.6 or 5
D-C Output Current, amps	100	200	100	8,333 or 1,000

The filter parametric data were prepared for the silicon transistor and controlled rectifier (SCR) converters only. These data were prepared using a single inductance-capacitance filter for all of the single value d-c output voltage systems. The filter network for the dual value 0.6-and 5-kilovolt output voltage systems use a total of eight separate inductance-capacitance filters; one for each bridge rectifier assembly.

Electrical Design

Operation and Circuit Description

The purpose of the output filter is to reduce the voltage ripple on the rectified d-c bus to a value which is compatible with the requirements of the load.

The filter selected for this study is a conventional low pass inductance-capacitance network, which is of the inductance input type with the capacitor in shunt across the load. It has the advantage of providing relatively good voltage regulation, high transformer utilization factor, and low diode peak currents.

For the filter selected, the capacitor reactance is usually negligible compared to the load impedance. This causes the alternating components of current to be shunted past the load, thereby eliminating them from the load. Also, the capacitive reactance is almost always lower than the inductance reactance, so that the ripple voltage appears across the inductor and not across the capacitor and load.

Design Criteria

The filter parametric data is based on the following;

1. The ripple voltage which will be reduced to a level of 4 percent RMS, is the only criterion used to determine the filter parameters. This value agrees with NASA's present requirements for electric-propulsion-engine circuits.
2. The capacitor voltage rating is at least 2.5 times the peak capacitor voltage under normal system operation. The capacitor dielectric is film plus paper.
3. The capacitor case temperature is maintained at 203°F (95°C) which is a 25 percent derating from the supplier's specified maximum of 125°C.
4. The inductor losses are based on a temperature that results from using a liquid metal cooling system with inlet temperatures in excess of 700°F.

Parametric Data

The filter parameters for all of the power-converter systems are determined from the RMS voltage-ripple values calculated from the rectified inverter-output waveforms. The necessary attenuation to obtain the desired ripple voltage, over a range of inverter frequencies of 50 to 5000 cycles per second, was determined. To restrict the selection of the numerous L-C filter combinations to a single choice it was necessary to use an additional constraint. Therefore, in addition to the attenuation requirements, the low pass L-C filter was required to meet the damping factor of one at full rated load. This latter condition was reflected as the ratio of L-C as a function of a resistive load.

Tables 30 through 33 list the component quantities, size, weight, and power losses of the output filter for the silicon transistor and controlled rectifier (SCR) inverter circuits.

Figures 44 and 45 represent the converter system percent output ripple voltage without a filter and the filter power losses of the 1,000-kilowatt converters as a function of the inverter circuit frequency. The curves of Figure 46 show the output-filter losses compared to converter output power at an inverter frequency of 1000 cycles per second.

For the four percent voltage ripple limit, Figure 44 shows that an output filter is not required for transistor and controlled rectifier inverter circuits at or below inverter frequencies of 290 and 100 cycles per second, respectively. Therefore, filter data for the transistor inverter circuits at inverter frequencies of 50, 100, and 200 cycles per second are not tabulated in Tables 30 and 31. Also, filter data for the controlled-rectifier inverter circuits at inverter frequencies of 50 and 100 cycles per second are not tabulated in Tables 32 and 33.

TABLE 30

OUTPUT FILTERS FOR TRANSISTOR CONVERTERS

*Inverter Circuit Frequency (cps)	500kw Converter				1000kw Converter			
D-C Bus Volts (kv)	500	1000	2000	5000	500	1000	2000	5000
D-C Load Current (amperes)	5	5	5	5	5	5	5	5
Capacitor	100	100	100	100	200	200	200	200
Capacitance (microfarads)	2.2	1.1	0.75	0.44	4.4	2.4	1.6	0.8
Watts Loss/Capacitor	0.126	0.25	0.5	1.25	0.126	0.25	0.5	1.25
Total Qty. Capacitors	44	22	15	9	80	48	32	16
Total Capacitor Watts	0.554	0.55	7.5	11.25	10.1	12	16	20
Total Capacitor Wt. (lbs)	22	11	7.5	4.5	40	24	16	8
Dimensions/Capacitor	Dia. = 1.344", Lgth. = 5.75"				Dia. = 1.344", Lgth. = 5.75"			
Inductor	22	11	7.5	4.5	10	6	4	2
Inductance (millihenries)	1520	1140	965	690	1930	1540	1310	905
Inductor Losses (watts)	152.6	90.2	63.4	43	230	156.6	111.8	66
Inductor Electromagnetic Wt. (lbs)	1450	1050	510	370	2400	1520	1100	600
Inductor Space Volume (in ³)	1520	1140	972	701	1940	1552	1326	925
Total Filter Losses (watts)	174.6	101.2	70.9	47.5	270	180.6	127.8	74
Total Filter Component Wt. (lbs)								

*Filter data for inverter frequencies of 50, 100, and 200 cps are not tabulated because the voltage ripple is below the 4 percent limit at these frequencies. Therefore, filters are not required.

TABLE 31

OUTPUT FILTERS FOR TRANSISTOR CONVERTERS

*Inverter Circuit Frequency (cps)	2000kw Converter				**5000kw Converter			
	500	1000	2000	5000	500	1000	2000	5000
D-C Bus Volts (kv)	20	20	20	20	0.625	0.625	0.625	0.625
D-C Load Current (amperes)	100	100	100	100	1000	1000	1000	1000
Capacitor								
Capacitance (microfarads)	0.53	0.312	0.2	0.1	192	96	64	32
Watts Loss/Capacitor	0.1	0.2	0.4	1	0.019	0.0392	0.0775	0.197
Total Qty. Capacitors	212	126	80	40	3072	1536	1024	512
Total Capacitor Watts	21.2	25.2	32	40	58.3	60	79.5	100.1
Total Capacitor Wt. (lbs)	131	78	49.6	24.8	928	464	310	155
Dimensions/Capacitor	Dia. 1.344", Lgth. 7.125"				Dia. 1.344", Lgth. 3.5"			
Inductor								
Inductance (millihenries)	85	50	30	15	0.30	0.15	0.10	0.05
Inductor Losses/Section (watts)	2750	2150	1700	1130	1700	1200	1000	730
Inductor Electromagnetic Wt./Sec.	532	355	245	145	188	110	80	46
Inductor Space Vol./Sec. (in ³)	6400	4100	2650	1450	1880	1025	730	400
Total Inductor Losses (watts)	2750	2150	1700	1130	13,600	9600	8000	5840
Total Inductor Weight (lbs)	532	355	245	145	1504	880	640	368
Total Inductor Space Vol. (in ³)	6400	4100	2650	1450	15,040	8200	5840	3200
Total Filter Losses (watts)	2771	2175	1732	1170	13,658	9660	8080	5940
Total Filter Component Wt. (lbs)	663	433	294.6	169.8	2432	1344	950	523

* Filter Data for inverter frequencies of 50, 100, and 200 cps are not tabulated because the voltage ripple is below the 4% limit at these frequencies. Therefore, filters are not required.

**Inductor and capacitor data is presented for separate filter sections of a total of 8 required. Each filter is connected to a separate rectifier assembly for the total of 8 used. Each filter is rated for 625 kw at 625 volts d-c; this is the condition for all 8 rectifier and filter assemblies connected in series at a bus voltage of 5kv. Data of total losses, weight, and volume is a summation of 8 separate filters.

TABLE 32

OUTPUT FILTERS FOR SCR CONVERTERS

*Inverter Circuit Frequency (cps)	500kw Converter					1000kw Converter				
	200	500	1000	2000	5000	200	500	1000	2000	5000
D-C Bus Volts (kv)	5	5	5	5	5	5	5	5	5	5
D-C Load Current (amperes)	100	100	100	100	100	200	200	200	200	200
Capacitor										
Capacitance (microfarads)	5.5	2.75	1.6	0.9	0.45	11.6	6	3.2	2	1
Watts Loss/Capacitor	0.05	0.126	0.25	0.5	1.25	0.05	0.126	0.25	0.5	1.25
Total Qty. Capacitors	110	55	32	18	9	232	120	64	40	20
Total Capacitor Watts	5.5	6.9	8	9	11.3	5.8	15.1	16	20	25
Total Capacitor Wt. (lbs)	55	27.5	16	9	4.5	116	60	32	20	10
Dimensions/Capacitor	Dia. = 1.344", Lgth. = 5.75"									
Inductor										
Inductance (millihenries)	55	27.5	16	9	4.5	29	15	8	5	2.5
Inductor Losses (watts)	2220	1620	1333	950	690	3150	2330	1740	1400	1000
Inductor Electromagnetic Wt. (lbs)	300	173	113	74	43	530	315.5	195	135	79
Inductor Space Vol. (in ³)	3150	1730	1100	670	370	6000	3400	2000	1400	730
Total Filter Losses (watts)	2226	1627	1341	959	701	3156	2345	1756	1420	1025
Total Filter Component Wt. (lbs)	355	200	129	83	47.5	646	375.5	227	155	89

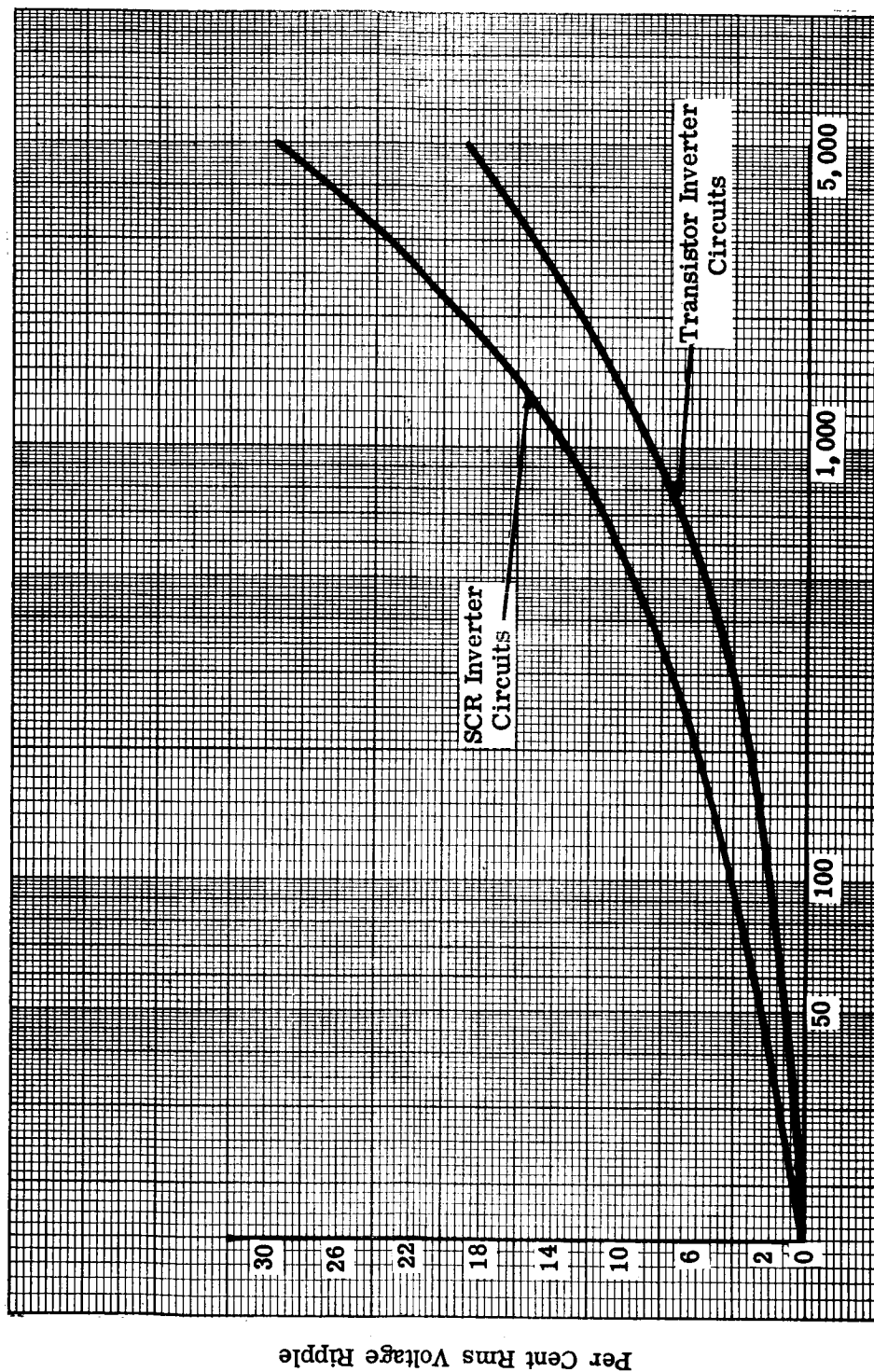
*Filter data for the inverter frequency of 50 and 100 cps is not tabulated because the voltage ripple is below the 4% limit at this frequency. Therefore, a filter is not required.

TABLE 33
OUTPUT FILTERS FOR SCR CONVERTERS

	2000 kw Converter						**5000 kw Converter					
	200	500	1000	2000	5000		200	500	1000	2000	5000	
*Inverter Circuit Frequency (cps)												
D-C Bus Volts (kv)	20	20	20	20	20		0.625	0.625	0.625	0.625	0.625	
D-C Load Amperes	100	100	100	100	100		1000	1000	1000	1000	1000	
Capacitor												
Capacitance (microfarads)	1.8	0.94	0.437	0.25	0.125		400	208	128	80	40	
Watts Loss/Capacitor	0.04	0.1	0.2	0.4	1		0.0078	0.019	0.0392	0.0775	0.197	
Total Qty. Capacitors	720	376	176	100	50		6400	3328	2048	1280	640	
Total Capacitor Watts	28.8	37.6	35.2	40	50		49.6	63.3	80.3	99.3	126	
Total Capacitor Wt. (lbs)	446	233	109	62	31		1930	1000	619	386	193	
Dimensions/Capacitor	Dia. = 1.344", Lgth. = 7.125"						Dia. = 1.344", Lgth. = 3.5"					
Inductor												
Inductance (millihenries)	290	150	70	40	20		0.625	0.325	0.200	0.125	0.062	
Inductor Losses/Section (watts)	4000	3700	2500	1930	1400		2380	1800	1520	1150	840	
Inductor Electromagnetic Wt./Sec. (lbs)	1280	815	455	300	180		330	215	153	100	58	
Inductor Space Vol./Sec. (in ³)	17500	10200	5400	3350	1720		3550	2150	1450	950	520	
Total Inductor Losses (watts)	4000	3700	2500	1930	1400		19040	14400	12160	9200	6720	
Total Inductor Wt. (lbs)	1280	815	455	300	180		2640	1720	1224	800	464	
Total Inductor Space Vol. (in ³)	17500	10200	5400	3350	1720		28400	17200	11600	7600	4160	
Total Filter Losses (watts)	4029	3738	2535	1970	1450		19090	14463	12240	9299	6846	
Total Filter Component Wt. (lbs)	1726	1048	564	362	211		4570	2720	1843	1186	657	

* Filter data for the inverter frequency of 50 and 100 cps is not tabulated because the voltage ripple is below the 4% limit at this frequency. Therefore, a filter is not required.

**Inductor and capacitor data is presented for separate filter sections of a total of 8 required. Each filter is connected to a separate rectifier assembly for the total of 8 used. Each filter is rated for 625 kw at 625 volts d-c; this is the condition for all 8 rectifier and filter assemblies connected in series at a bus voltage of 5kv. Data of total losses, weight, and volume is a summation of 8 separate filters.



Inverter Switching Frequency - Cycles Per Second

FIGURE 44

Converter Output Ripple
Vs. Inverter Switching Frequency
- Without Filter -

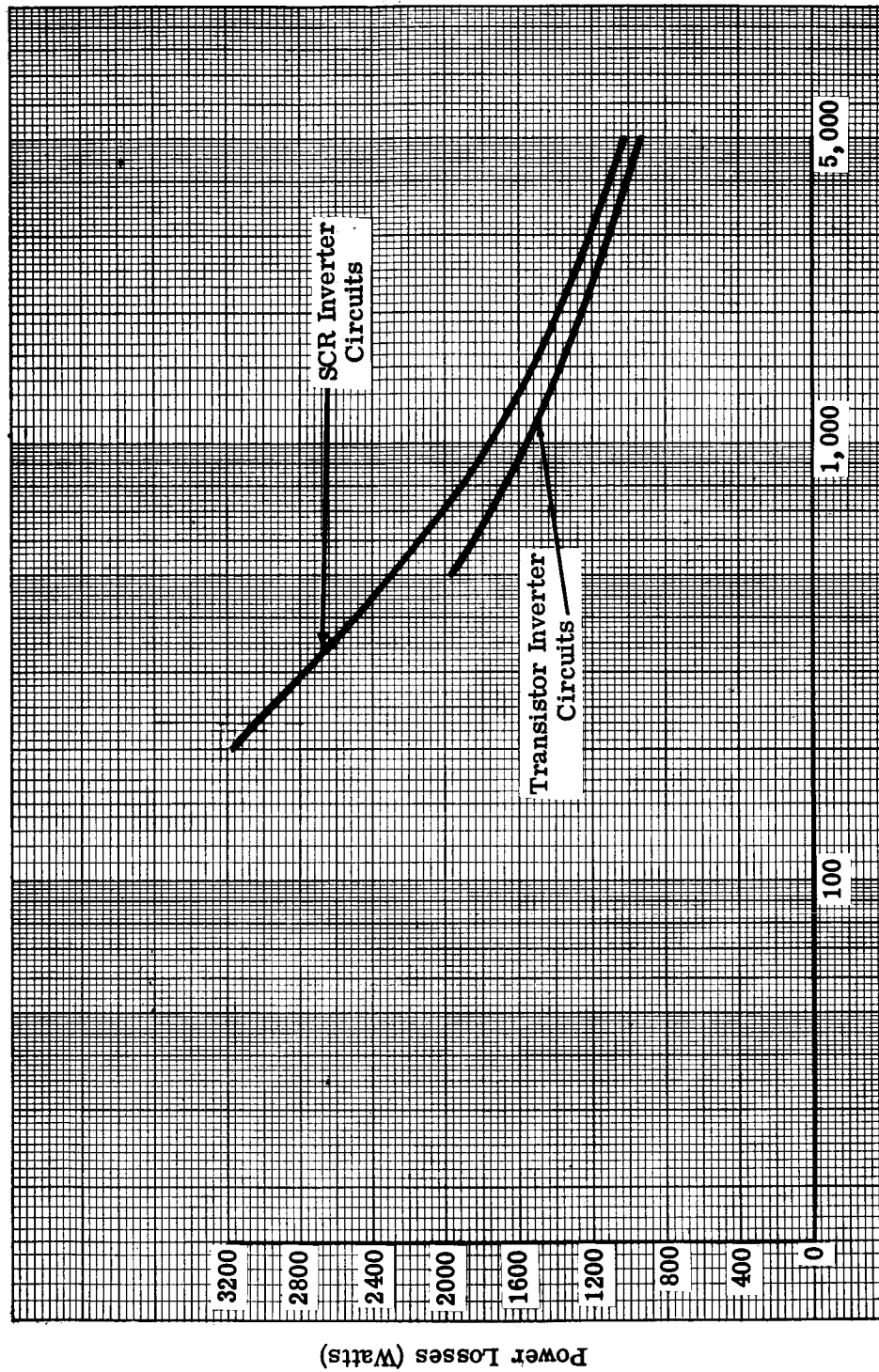


FIGURE 45
Inverter Switching Frequency - Cycles Per Second

Output Filter
1 Megawatt
Power Losses Vs. Inverter Switching Frequency

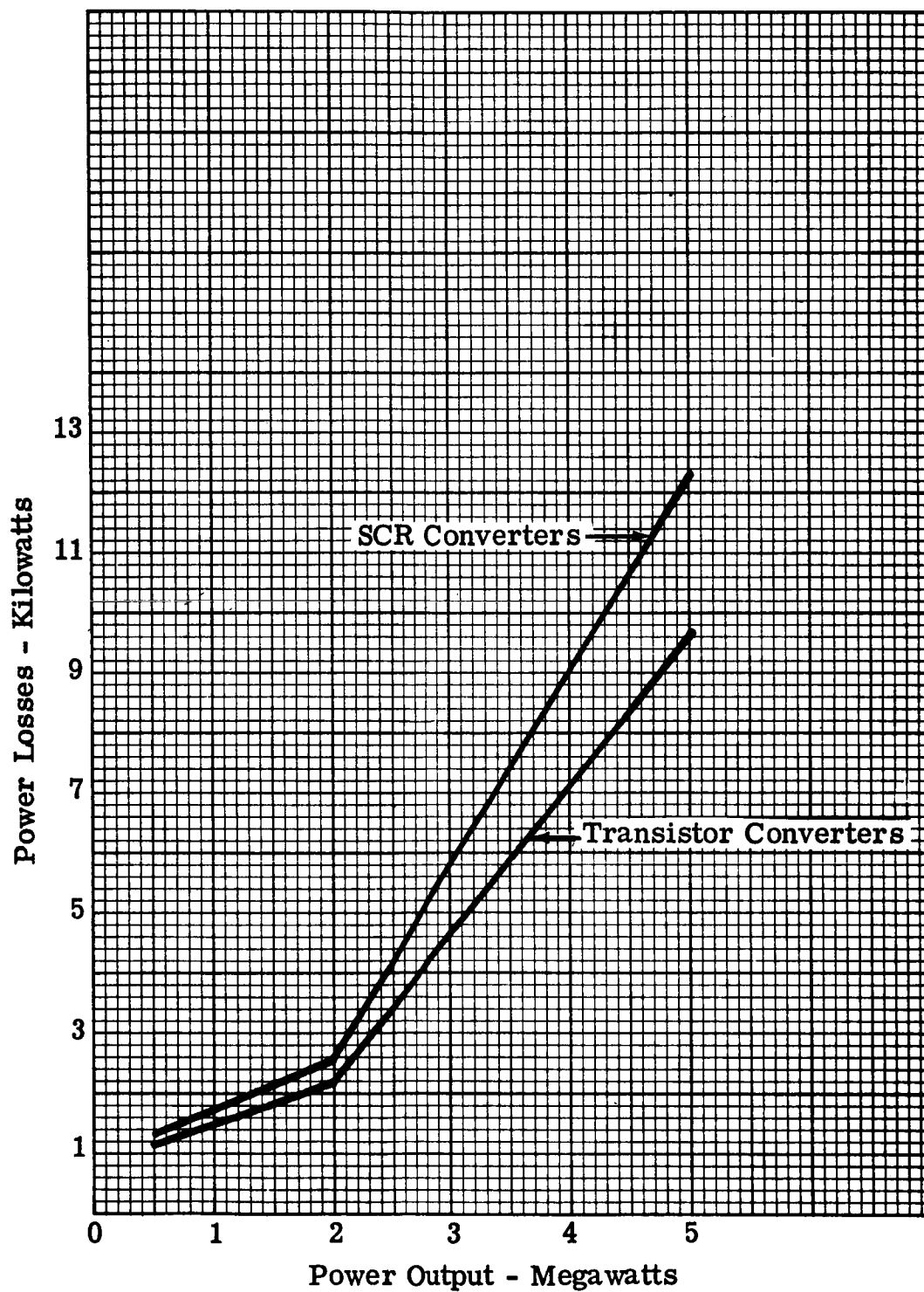


FIGURE 46

Output Filter
1000 Cycles Per Second
Power Losses Vs. Power Output

Problem Areas

The inductors of the output filter are capable of being cooled by liquid metal coolants at temperatures in excess of 700° F. Capacitors capable of operating at this coolant temperature are not available, and probably will not be available by 1968 at the present normal rate of development. This problem, for this application, was circumvented by using 125°C (257°F) capacitors, with an appropriate cooling system, which are isolated from the high temperature inductor system.

Analysis and Recommendations

The curve of Figure 44 shows that the voltage ripple on an unfiltered converter d-c output bus increased with increasing inverter frequency. This curve also shows that of the two-semiconductor inverter-switching circuit components used, the silicon-controlled rectifiers as compared to the transistors produce correspondingly greater magnitudes of voltage ripple over the frequency range. The reason for this is that the greater turn-on and turn-off times required for the controlled rectifiers results in a relative poorer quality rectified waveform. Therefore, the controlled-rectifier power conditioning equipment requires larger and heavier filters with higher power losses. This is substantiated in Tables 28 through 31 and Figures 45 and 46. The curves of Figure 46 are not shown as a smooth curve since the 5-megawatt system has a dual voltage output while the remaining converters have a single voltage value output.

Although the voltage ripple increases with increasing inverter switching frequency, the filter size, weight, and losses decrease with frequency because both capacitance and inductance become smaller.

To provide a filter capacitor cooling system which is compatible with the operating temperature of the inductor, it is desirable to develop capacitors capable of operating at 700°F coolant temperatures. These capacitors should be capable of operating at a dissipation factor of approximately one percent and with a bulk factor approaching that of the existing lower voltage, lower temperature capacitors.

Mechanical Design

Description

Output filter capacitors are clip-mounted to cold plates which are an integral part of the structure. The structure and coolant conduits are made of beryllium. Adhesive bonding is used between capacitors, clips, and cold plate to reduce thermal resistance across the joints in a space environment.

Inductor cores are mounted to support rails of which coolant conduits are an integral part. Inductors are potted to facilitate cooling by conduction to the coolant conduits. Coolant conduits and structure are of columbium.

Capacitors and inductors are mounted on separate cooling circuits, and thermally insulated from each other to maintain the capacitor body temperature at 95°C, while taking advantage of the inductor allowable maximum temperature of 550°C. Coolant is eutectic NaK.

Design Criteria

The following basic design criteria are used to calculate the required parametric data.

1. The coolant was assumed to be eutectic NaK, which has a specific heat of 0.210 Btu/lbs.-°F, and a density of 0.0306 lbs/in.³. Convection temperature drop was assumed to be 1°C.
2. Beryllium for use in coolant tubes and cold plate has the following characteristics:

Density	0.067 lbs/in ³
Thermal Conductivity	87 Btu/hr-ft-°F
Thermal Expansion	6.4×10^{-6} in/in/°F
3. Columbium for use in coolant tubes and cold plate has the following characteristics:

Density	0.310 lbs/in ³
Thermal Conductivity	31.5 Btu/hr-ft-°F
Thermal Expansion	3.82×10^{-6} in/in/°F
4. Adhesive bonding is .002 inch thick, with a thermal conductivity of 0.227 Btu/hr-ft-°F.
5. Minimum achievable thermal resistance between two surfaces not bonded together is 0.2°C/watt in a space environment.
6. Capacitor case temperature is 95°C; inductor maximum temperature is 550°C, with a 150°C rise between the coolant and the peak temperature.
7. Weight of capacitor supporting structure is assumed to vary from 20% of the total capacitor package weight for heavier units to 30% for the lightest unit, the 0.5 megawatt 5000 cycle per second design. Total inductor package weight,

including insulation, structure, and cooling provisions is assumed to be 1.9 times the electromagnetic weight.

Parametric Data

Weights and volumes for output filter designs for transistor converters are given in Table 34. Those for SCR converters are given in Table 35. Variation of weight with power rating is given in Figure 47 for filters used with transistor converters and in Figure 48 for those used with SCR converters. Variation of volume with power rating are given in Figures 49 and 50 for the transistor and controlled-rectifier converters, respectively. Figure 51 shows variation of weight with frequency for the one-megawatt designs. Figure 52 presents variation of coolant inlet temperature with flow rate for capacitors in the one megawatt-designs at a frequency of 1000 cycles per second. Figure 53 presents this variation for inductors.

Problem Areas

Problem areas anticipated are the same as those previously described in the inverter circuit and power transformer portions of this report. In summary they are:

1. Development of techniques for use of beryllium.
2. Development of reliable adhesive bonds.
3. Development of inductors for high-temperature application, particularly in the choice of insulation materials.
4. Development of potting compounds for use at high temperature in space environment.
5. Thermal stresses.

Analysis and Recommendations

From comparison of output filter parameters in Tables 34 and 35, the one-megawatt designs have the lowest specific weight of those considered, and appear most attractive. Filters for transistor converters are slightly lighter and smaller than those for SCR converters, and are thus desirable. However, final choice of a design point will depend on consideration of all the electrical and mechanical parameters of the complete power system.

For the one-megawatt designs curves of weight versus frequency and coolant-inlet temperature versus flow rate at 1000 cycles per second are presented. From the curves of weight versus frequency, a frequency above one kilocycle per second is recommended.

From the curves of inlet temperature versus flow rate, a flow rate above about 0.25 pounds per minute is sufficient for the

TABLE 34

OUTPUT FILTER WEIGHTS AND VOLUMES FOR TRANSISTOR CONVERTER

Power Level (megawatts)	0.5	1.0	2.0	5.0
Frequency	Total Weight (lbs)			
500 cps	342.5	527.0	1288	4560
1000 cps	200.0	354.0	844	2539
2000 cps	141.0	251.0	575	1810
5000 cps	94.6	146.8	332	1001
	Total Volume (cu.ft.)			
500 cps	2.07	3.56	10.05	53.40
1000 cps	1.29	2.20	6.25	27.20
2000 cps	0.74	1.56	4.06	18.40
5000 cps	0.52	0.84	2.16	9.42
	Specific Weight (lbs/kw)			
500 cps	0.685	0.527	0.644	0.913
1000 cps	0.400	0.354	0.422	0.508
2000 cps	0.282	0.251	0.288	0.362
5000 cps	0.189	0.147	0.166	0.200

TABLE 35

OUTPUT FILTER WEIGHTS AND VOLUME FOR SCR CONVERTERS

Power Level (megawatts)	0.5	1.0	2.0	5.0
Frequency	Total Weight (lbs)			
200 cps	694	1258	3320	8510
500 cps	392	732.5	2030	5110
1000 cps	254	443	1098	3490
2000 cps	164.8	303.5	706	2260
5000 cps	94.5	176	412	1257
	Total Volume (cu. ft.)			
200 cps	4.73	9.33	31.0	100.9
500 cps	2.52	5.09	16.93	58.5
1000 cps	1.56	2.92	8.45	36.8
2000 cps	0.94	1.94	5.08	23.3
5000 cps	0.52	1.02	2.62	11.9
	Specific Weight (lbs/kw)			
200 cps	1.388	1.258	1.660	1.702
500 cps	0.784	0.732	1.015	1.022
1000 cps	0.508	0.443	0.549	0.698
2000 cps	0.329	0.303	0.353	0.472
5000 cps	0.189	0.176	0.206	0.251

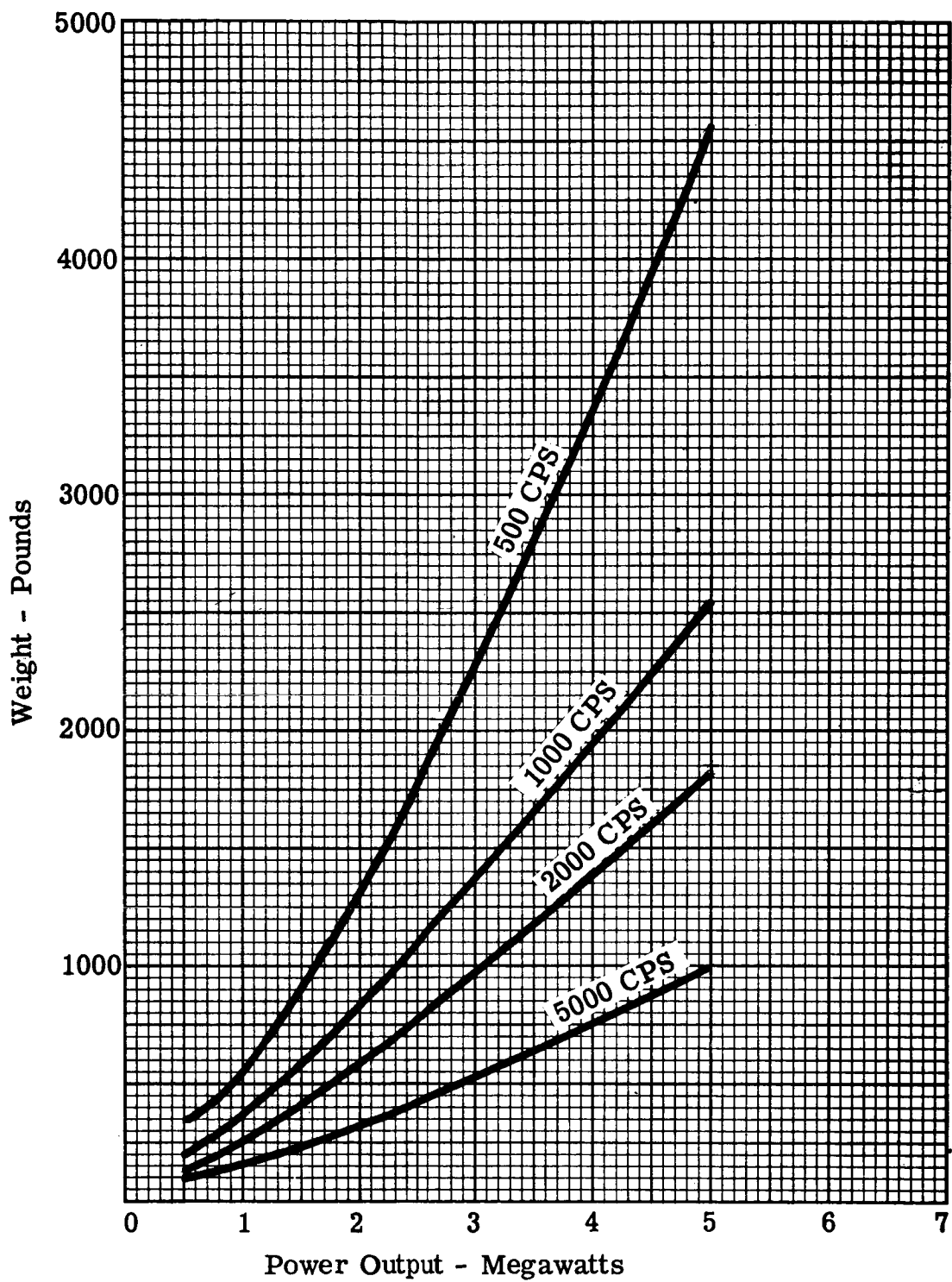


FIGURE 47
Output Filter
For Transistor Converters
Weight Vs. Power Output

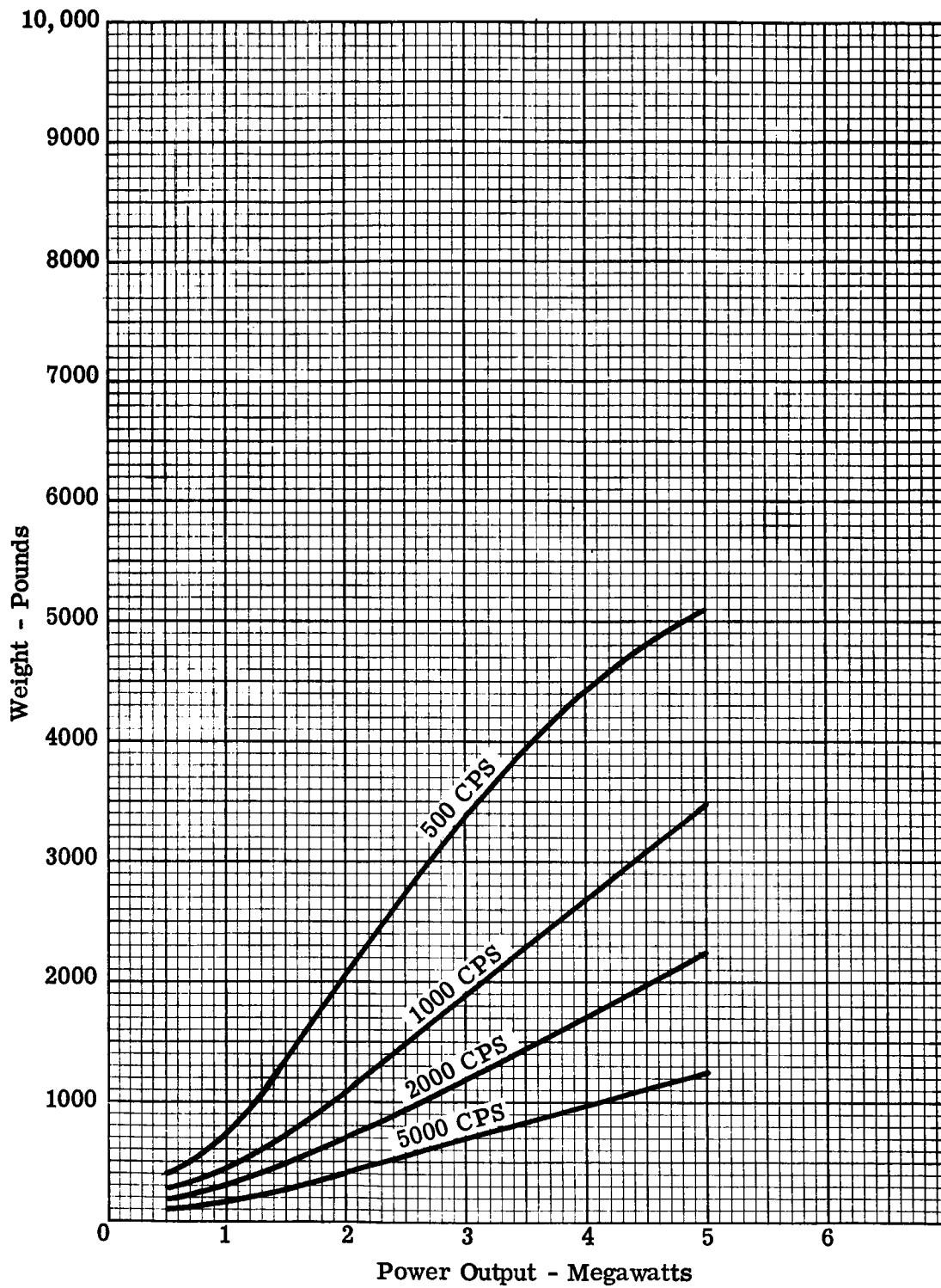


FIGURE 48

Output Filter
For SCR Converter
Weight Vs. Power Output

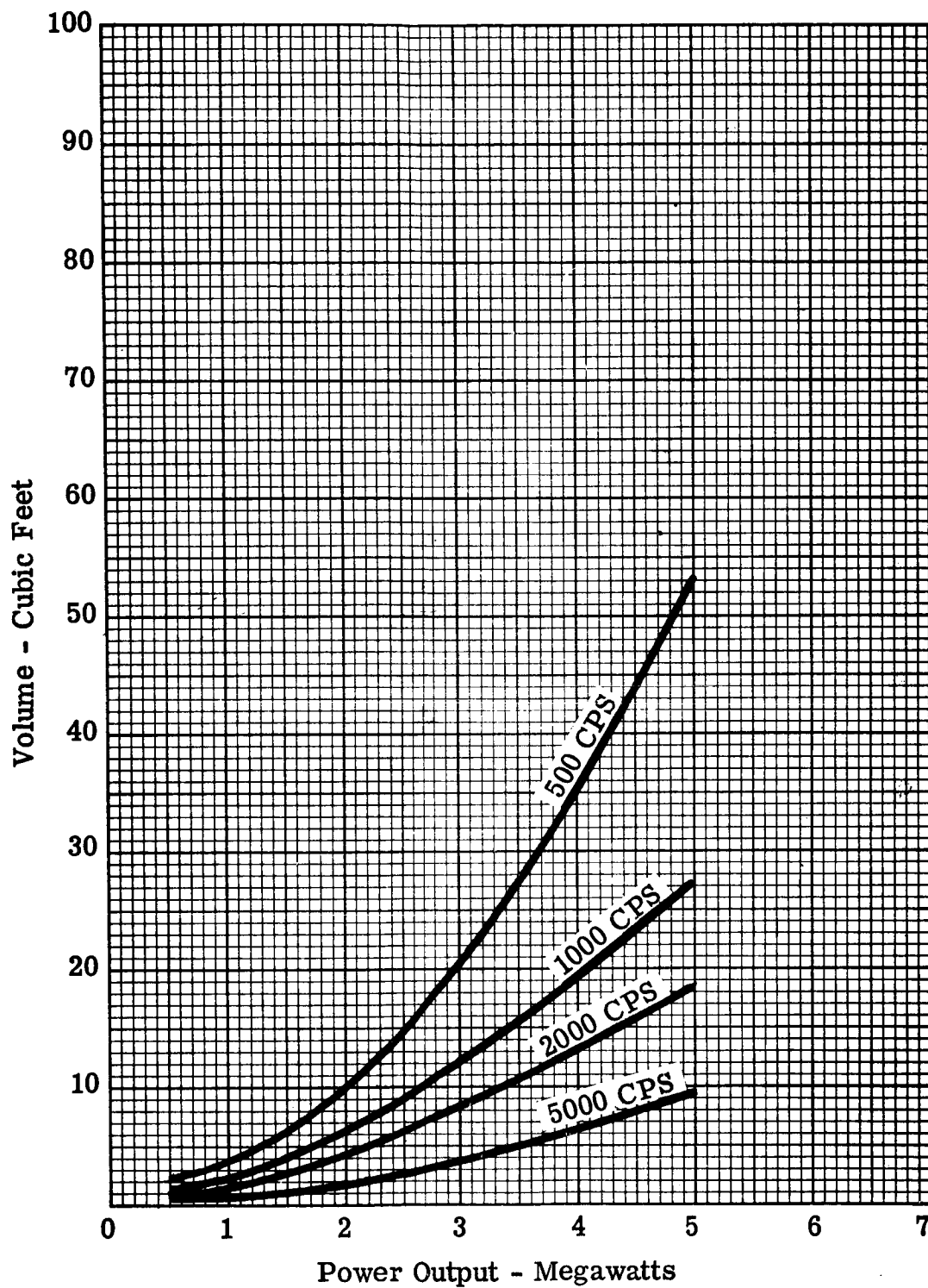


FIGURE 49
Output Filter
For Transistor Converters
Volume Vs. Power Output

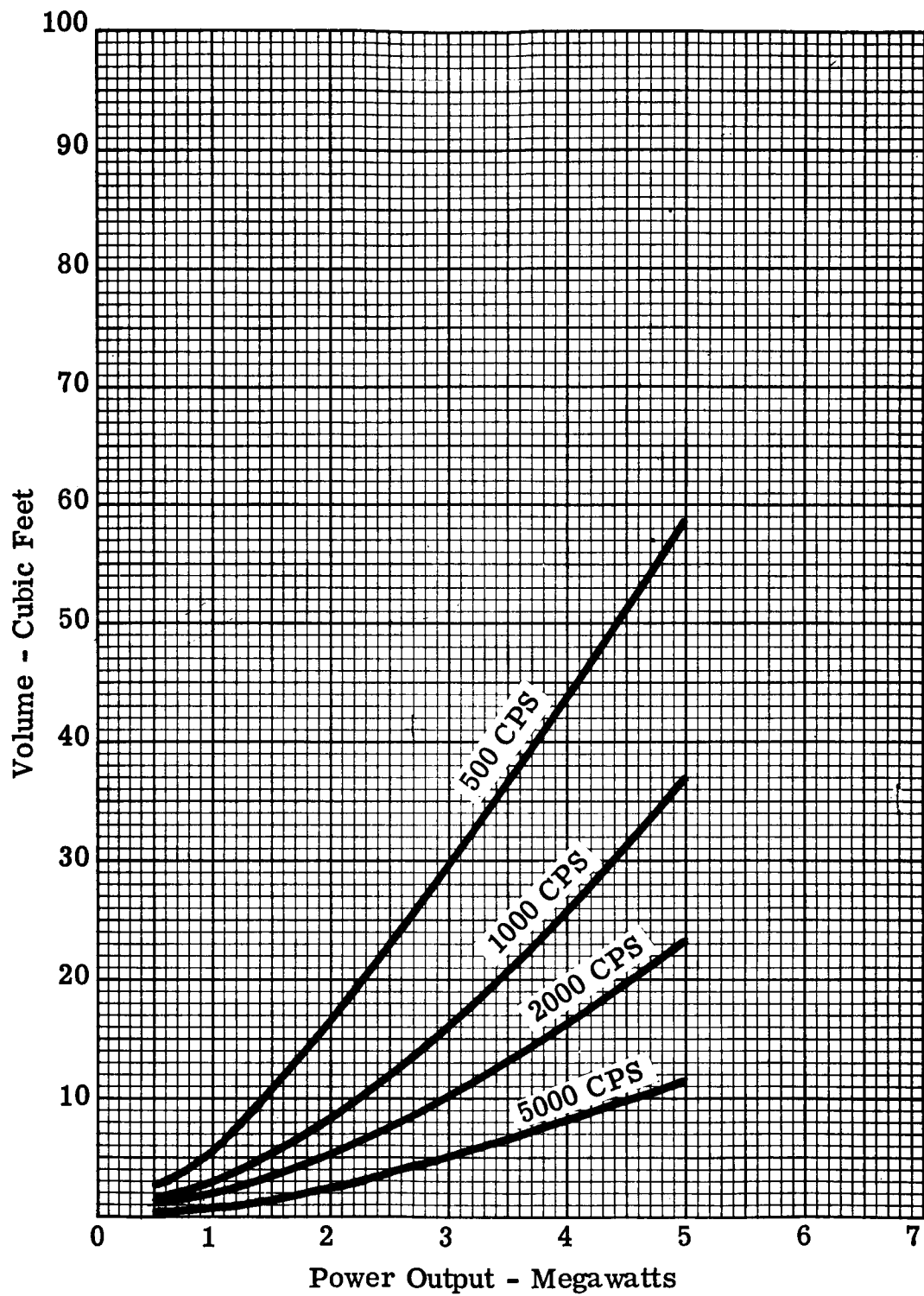


FIGURE 50
Output Filter
For SCR Converters
Volume Vs. Power Output

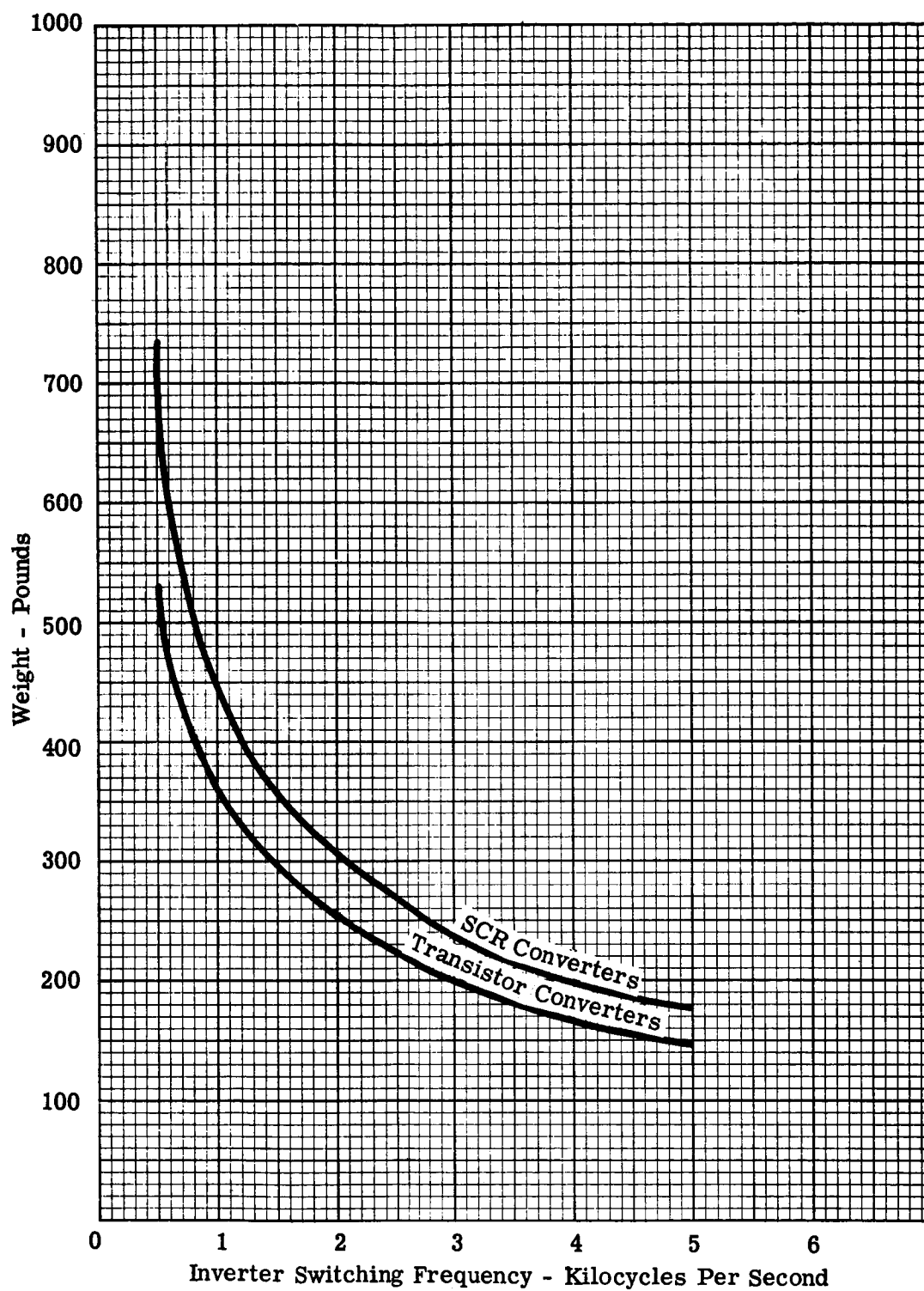


FIGURE 51
Output Filter
One Megawatt
Weight Vs. Inverter Switching Frequency

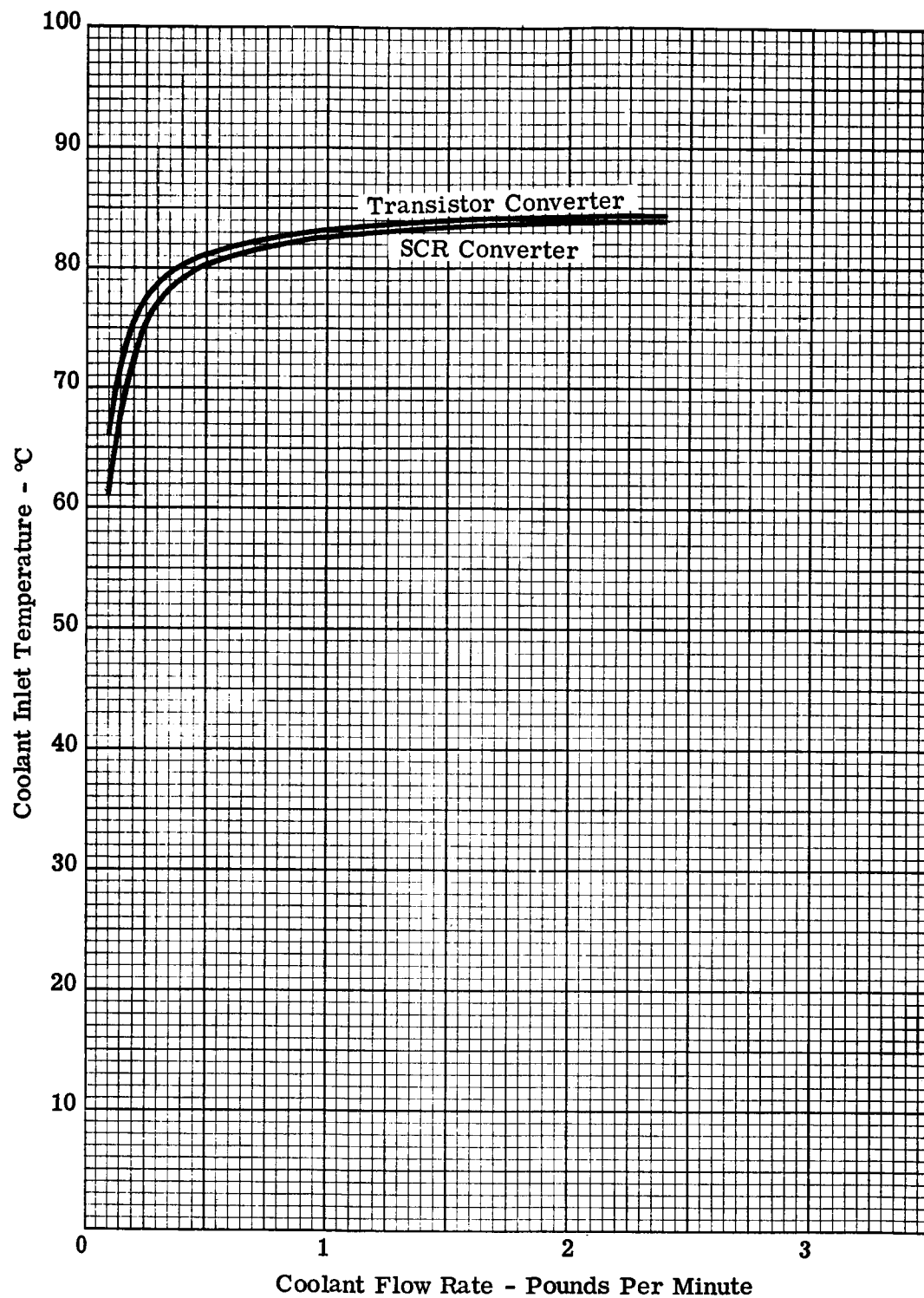


FIGURE 52

Output Filter Capacitor
1 Megawatt, 1000 Cycles Per Second
Coolant Inlet Temperature Vs. Coolant Flow Rate

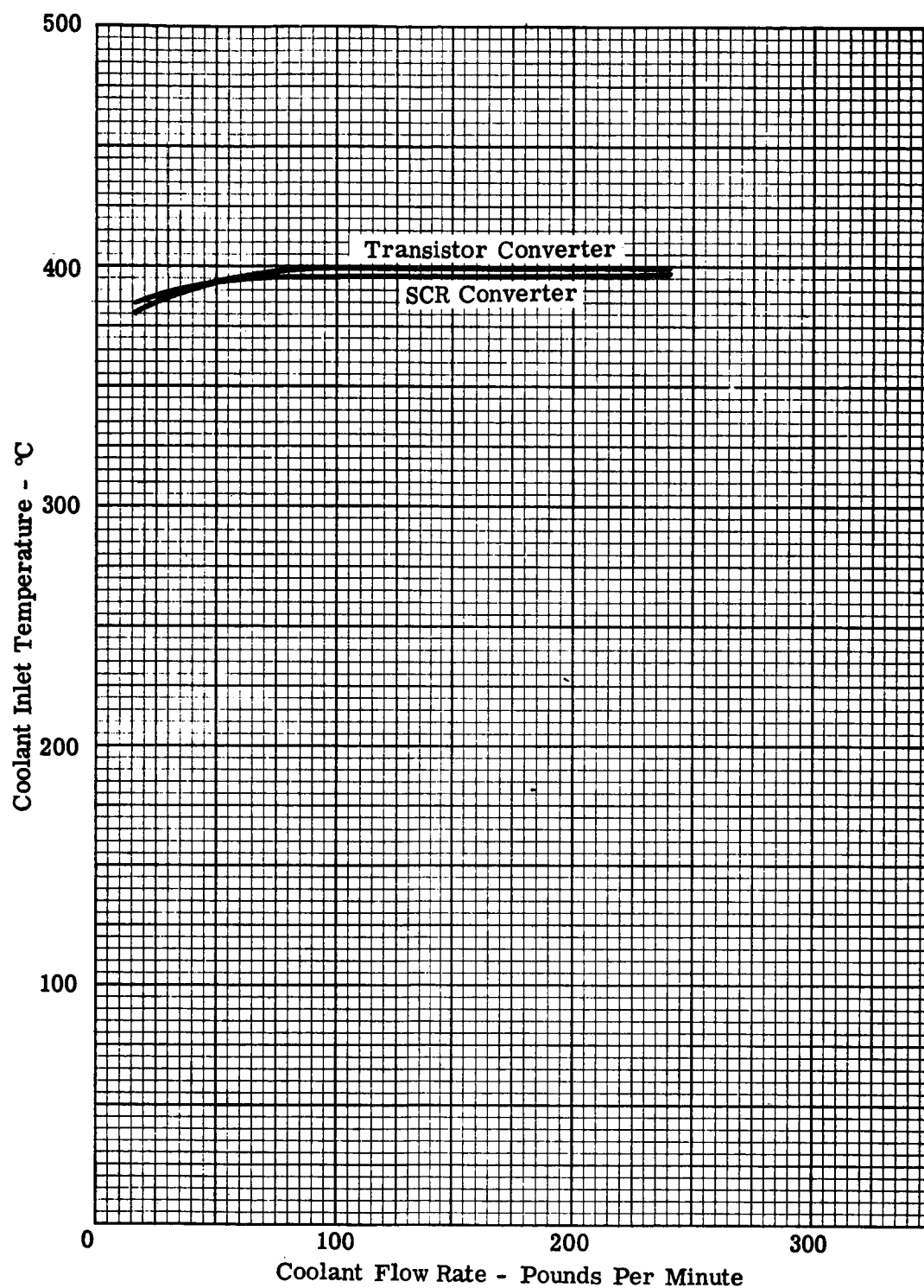


FIGURE 53
Output Filter Inductor
1 Megawatt, 1000 Cycles Per Second
Coolant Inlet Temperature Vs. Coolant Flow Rate

capacitors, and one above 30 pounds per minute is recommended for the inductors.

The use of beryllium is recommended for cold-plate structure in the capacitor section, and columbium in the inductor section. As noted in previous portions of this study, a program should be implemented to develop techniques for the use of beryllium.

F. SWITCHGEAR

Switchgear capable of operating in a space environment is required for switching the outputs of eight rectifier banks and filters from parallel to series connections for the 5000 kilowatt, 2 voltage value systems. Total rated output of the eight rectifier banks is 5000 kilowatts. Voltage for the parallel connection is 600 volts and 5000 volts for the series connection. Figure 54 is a schematic diagram of the rectifier banks and switchgear.

This section defines the requirements for switchgear needed in conjunction with the conversion equipment. No parametric data is presented in this study. It is assumed that results of the NASA switchgear program (contract number NAS3-2546) will provide information for the design of switchgear for this application.

Table 36 below lists required ratings for the switchgear.

TABLE 36
SWITCHGEAR RATINGS

	Total Rated Power (kw)	Total Rated Voltage (v.)	Total Rated Current (amps)	Volts Each Rect. Bank	Amps Each Rect. Bank
Parallel Position	5000	600	8333	600	1042
Series Position	5000	5000	1000	625	1000

The switchgear required consists of 14 poles, double throw. The rating of each contact must be 1042 amperes at 625 volts. Dielectric capability between the contacts and mounting frame must be 5000 volts operating. Overcurrent rating of each contact must be at least 400% rated current for one second since the rectifier banks are designed to withstand this overload.

An auxiliary contact is needed to provide logic to the voltage regulation circuit in the converter. With this logic the regulator will sense and control either 5000 or 600 volts on the output bus.

The contacts need not open or close under load if control is provided to stop the conversion equipment to interrupt power during switching. This might allow the switchgear to be designed small and light weight and is the preferable mode of operation. The power conversion equipment has been designed for this mode of operation.

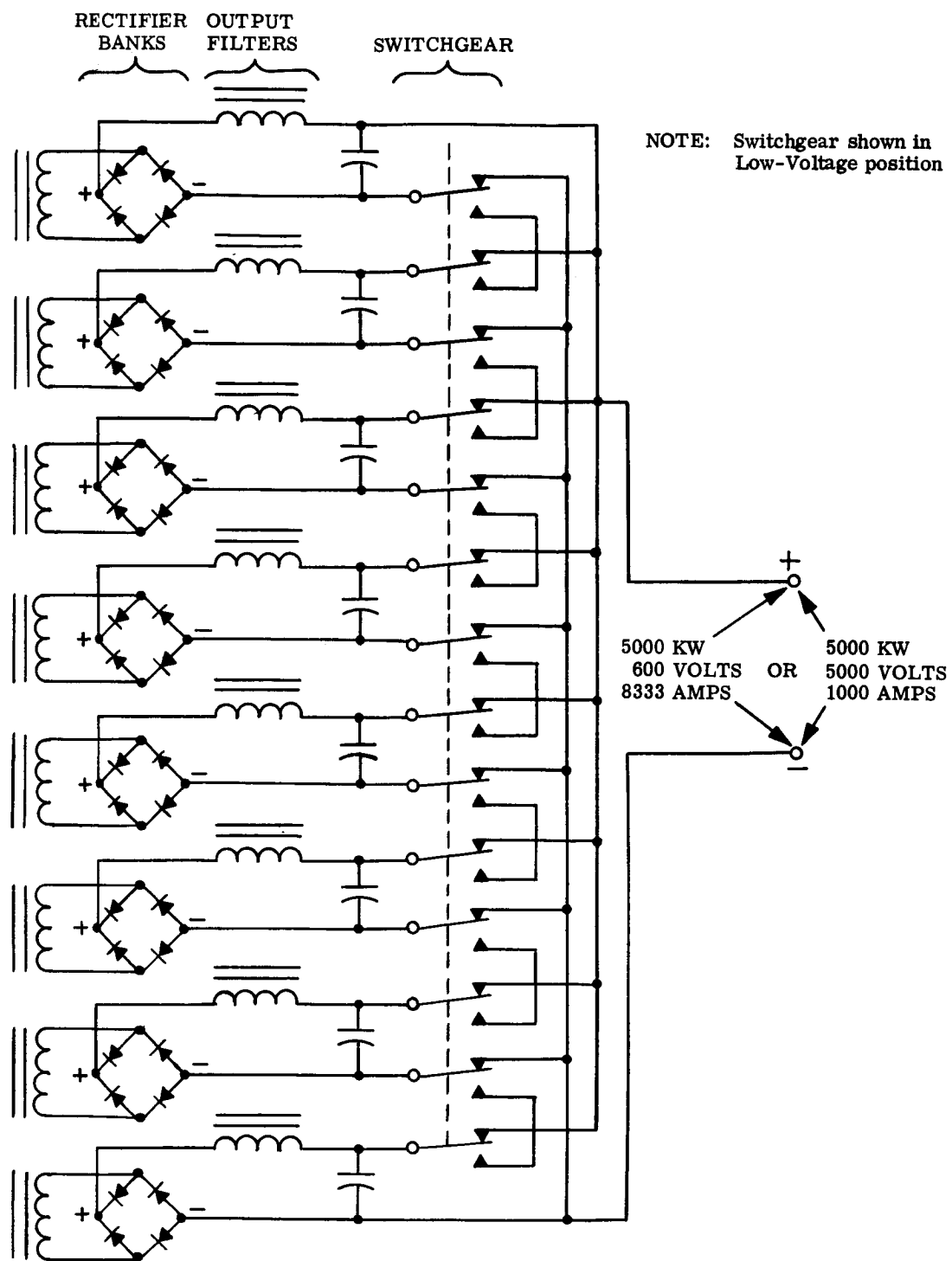


FIGURE 54
Switchgear and Associated Parts Schematic Diagram

Summary of Switchgear Requirements

Fourteen poles, double throw

Current rating per contact	1042 amperes, continuous
	4168 amperes, 1 second

Voltage rating per contact	625 volts
----------------------------	-----------

Dielectric requirement, to frame	5000 volts
----------------------------------	------------

Auxiliary contacts	One transfer contact
--------------------	----------------------

G. DRIVE AMPLIFIER

The drive amplifier performs two essential functions. It amplifies the square-wave signal from the frequency reference to a power level sufficient to drive the inverter, and it provides means to control several inverter modules for the purpose of regulating the output voltage of the power conversion equipment. The signals that actuate the drive amplifier come from the frequency reference oscillator and the voltage regulator. All the drive amplifiers use silicon-transistor switching elements.

Electrical Design

Description and Operation

For purposes of discussion the drive amplifiers are divided into three kinds. The first kind to be discussed are the drive amplifiers for the 20-volt input systems. Second, are the drive amplifiers for the 100-volt input systems, and third, are the drive amplifiers for the 300- and 600-volt systems. There is no evaluation of the drive amplifier for the high-temperature system because of insufficient information on tube drive requirements. A summary of the different designs is given in Table 37.

20-Volt Input Systems - The drive amplifier for the 20-volt, one-megawatt system will be described below in some detail. The 500 kilowatt system is similar to the megawatt design. The drive for the 20-volt, 2- and 5-megawatt systems is described separately.

Reference to Table 37, "Summary of Drive Amplifier Components", shows that the 1MW inverter requires 22 kilowatts of drive power. This amount of power is provided by 24 amplifier modules, which are similar to the transistor inverter modules. Eighteen of the amplifiers are used to drive the unregulated inverter modules, and the other six are used to drive the regulated inverter modules. The method of interconnection is shown in Figure 55. Several of the modules are interconnected for load sharing purposes. A discussion of this technique is presented later.

The six amplifier modules that drive the regulated portion of the inverter have the capability of being turned off by signals from the voltage regulator. When a rise in system output voltage occurs and exceeds +5%, these modules are turned off one at a time. Each time an amplifier module turns off, 46 regulated inverter modules are deprived of drive signals and stop operating. The output voltage falls in increments until it has returned to its correct value. The "turn-off" type amplifier modules are rendered controllable by the incorporation of two extra transistors, Q3 and Q4 in Figure 56. The remaining 18 amplifier modules are identical to the inverter modules of Figure 11-C presented in the "Inverter" section of this study.

TABLE 37

SUMMARY OF DRIVE AMPLIFIER COMPONENTS

System Input Voltage (volts)	20	20	20	20	20	100	100	100	100	100	300	300	300	300	300	600	600	600	600
System Power (megawatts)	.5	1	2	5		.5	1	2	5		.5	1	2	5		.5	1	2	5
Drive Amplifier Output Power (kw)	11	22	44	110		2.2	4.4	8.8	22		.12	.12	.24	1.0		.12	.12	.24	1.0
Stages of Amplification	1	1	2	2		1	1	1	1		0	0	0	0		0	0	0	0
Number of Plain Amplifiers	9	18	37	93		1	1	2	5		0	0	0	0		0	0	0	0
Number of Turn-Off Amplifiers	6	6	12	30		0	0	0	0		0	0	0	0		0	0	0	0
Number of Isolation Transformers	0	0	0	0		0	0	0	0		24	24	48	192		24	24	48	192
Number of Turn-Off Switches	0	0	0	0		12	12	12	112		6	6	6	56		6	6	6	56

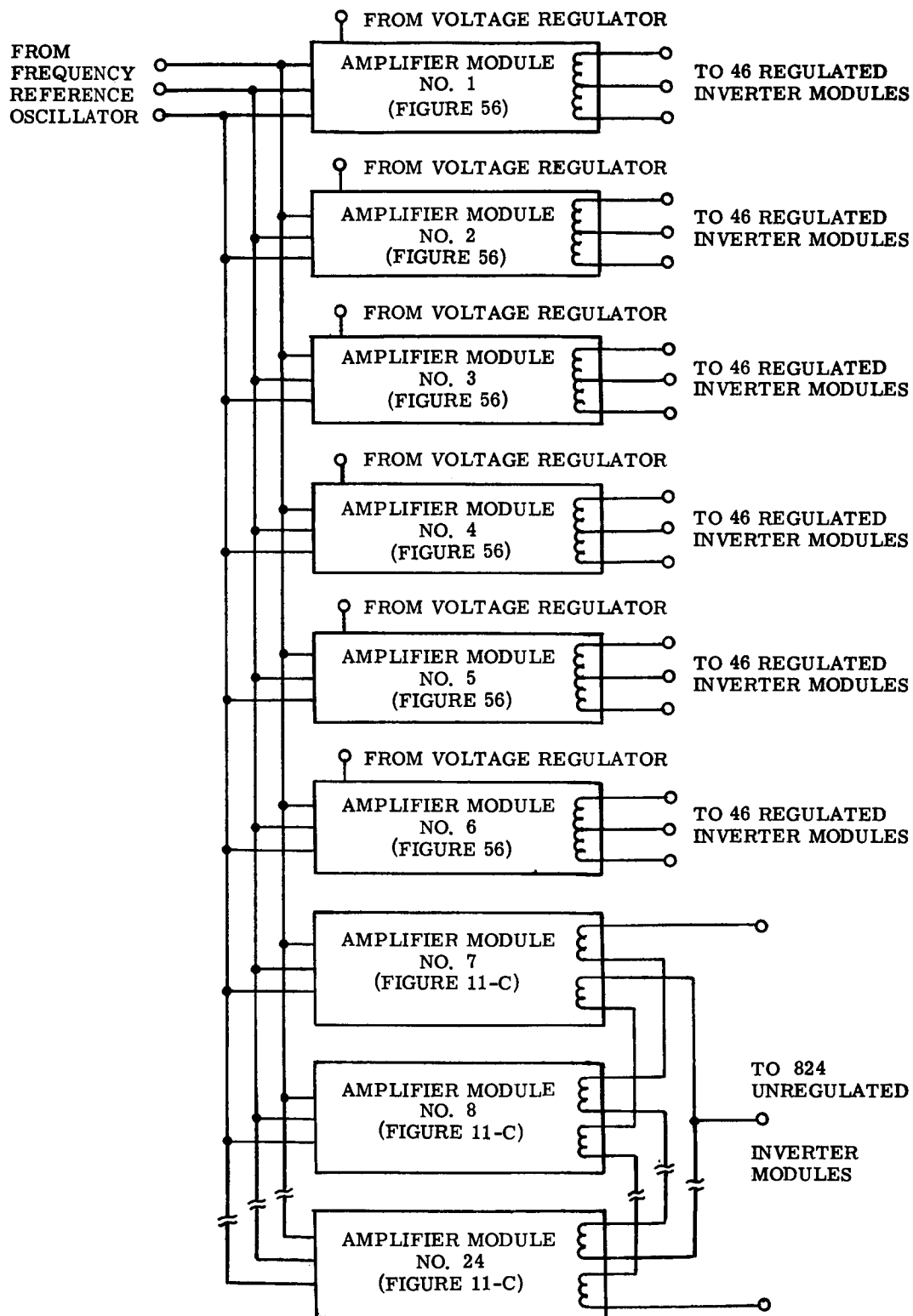


FIGURE 55
Drive Amplifier Functional Diagram
1 Megawatt, 20 Volt System

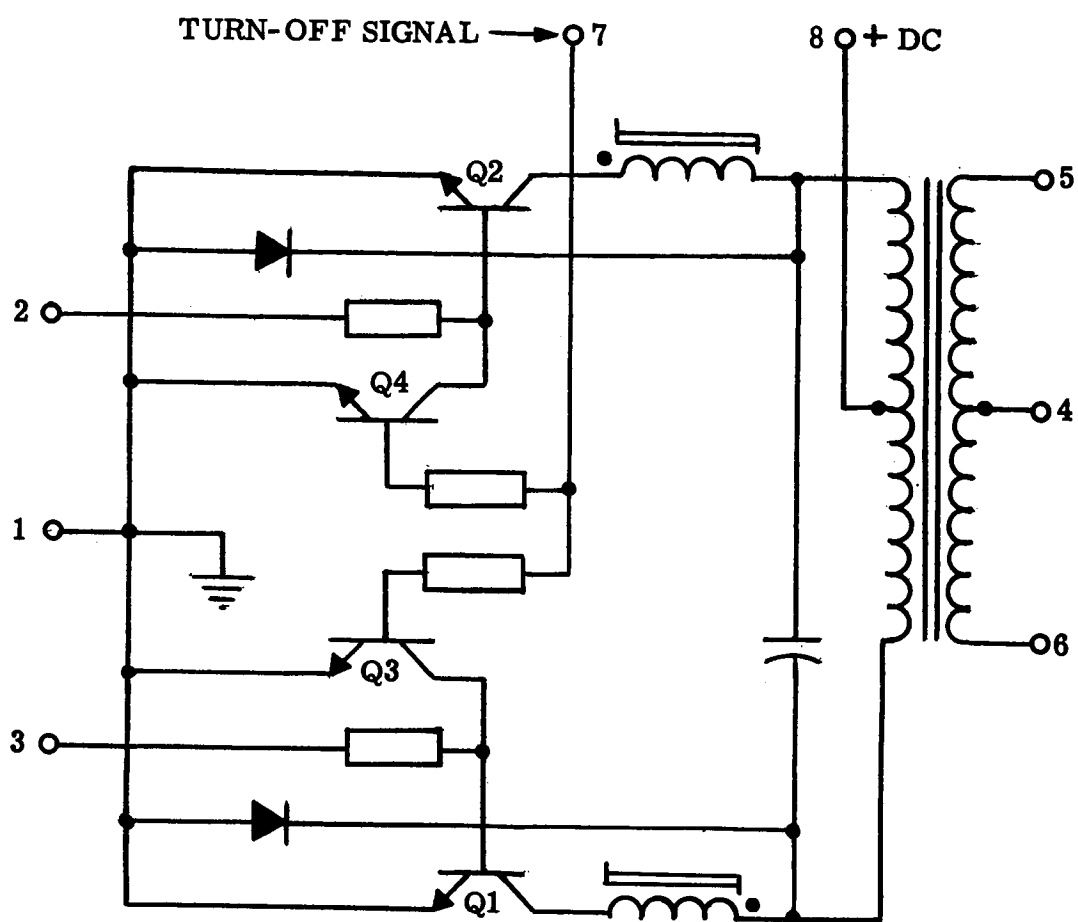


FIGURE 56
Turn-Off Type Amplifier Module

Dividing the inverter modules into seven groups, six regulated and one unregulated, was done to simplify the drive amplifier and to allow control of a group of inverter modules by a single low power signal from the voltage regulator. The precision of regulation by this method is $\pm 5\%$, which meets the requirements of ion thrusters as presently known.

As mentioned earlier, the drive amplifier for the 0.5-megawatt, 20-volt system is similar in principle to the 1-megawatt system. The main difference is that less output power is required, so that fewer amplifier modules are used. The number of amplifier modules and other components used in each system is shown in Table 38.

The drive amplifiers for the 20-volt, 2- and 5-megawatt systems differ in one important respect from the lower power units. An additional stage of amplification is used. The reason for this is that, to reach the power level required to drive these more powerful inverters, so many amplifier modules are required that the frequency reference oscillator cannot drive them all. Hence, additional amplifier modules are interposed between the frequency reference oscillator and the main bank of amplifiers. The 2 megawatt system requires 1 additional module, while the 5 megawatt system requires 3 additional modules. These additional modules are, again, the same as inverter modules.

100-Volt Input Systems - Reference to Table 38 shows that the 100-volt systems require up to five drive amplifier modules. The modules used are similar to the transistor inverter modules and do not have the turn-off feature. The philosophy of splitting the power inverter into seven groups of modules is followed again, as in the 20-volt systems.

In the 2- and 5-megawatt systems, where several drive amplifier modules are required, it is necessary to assure that load is shared equally. The method of doing this is shown in Figure 57 for the 2-megawatt system. Each module has two secondary windings. The secondary winding of one module is connected in series with the corresponding secondary of the other module. Each series connected pair of windings conducts during only one half-cycle of operation. One end of each series connection is brought to a common ground point. The free ends supply voltage to drive the inverter modules. The same principle is used in the 5-megawatt system, where 5 modules are used, and in all the 20-volt systems.

Control of the six groups of regulated inverter modules is accomplished by pairs of transistor switches connected in series with the drive leads to the inverter module groups. A signal from the voltage regulator opens or closes a pair of these switches, thus stopping or starting a group of inverter modules, to effect voltage regulation in the manner previously explained.

TABLE 38

DRIVE AMPLIFIERS - ELECTRICAL PARAMETERS

System Input Voltage (v)	20	20	20	20	20	100	100	100	100	100	300	300	300	300	300	600	600	600	600
System Rated Output (mw)	.5	1	2	5	5	.5	1	2	5	5	.5	1	2	5	5	.5	1	2	5
Drive Amplifier Output Power (kw)	11	22	44	110	22	2.2	4.4	8.8	22	22	.12	.12	.24	1.0	1.0	.12	.12	.24	1.0
Total Number of Amplifier Modules	15	24	49	123	5	1	1	2	5	5	0	0	0	0	0	0	0	0	0
Module Efficiency (%)	85	85	85	85	88	88	88	88	88	88	-	-	-	-	-	-	-	-	-
Heat Loss in Amplifier Modules (watts)	1650	3300	6750	16,900	2640	264	528	1056	2640	2640	0	0	0	0	0	0	0	0	0
Heat Loss in Isolation Transformers (watts)	0	0	0	0	0	0	0	0	0	0	48	48	96	384	384	48	48	96	384
Heat Loss in Turn-Off Switches (watts)	0	0	0	0	1120	108	216	432	1120	1120	24	24	24	224	224	24	24	24	224
Total Heat Loss in Drive Amplifier (watts)	1650	3300	6750	16,900	3760	372	744	1488	3760	3760	72	72	120	608	608	72	72	120	608

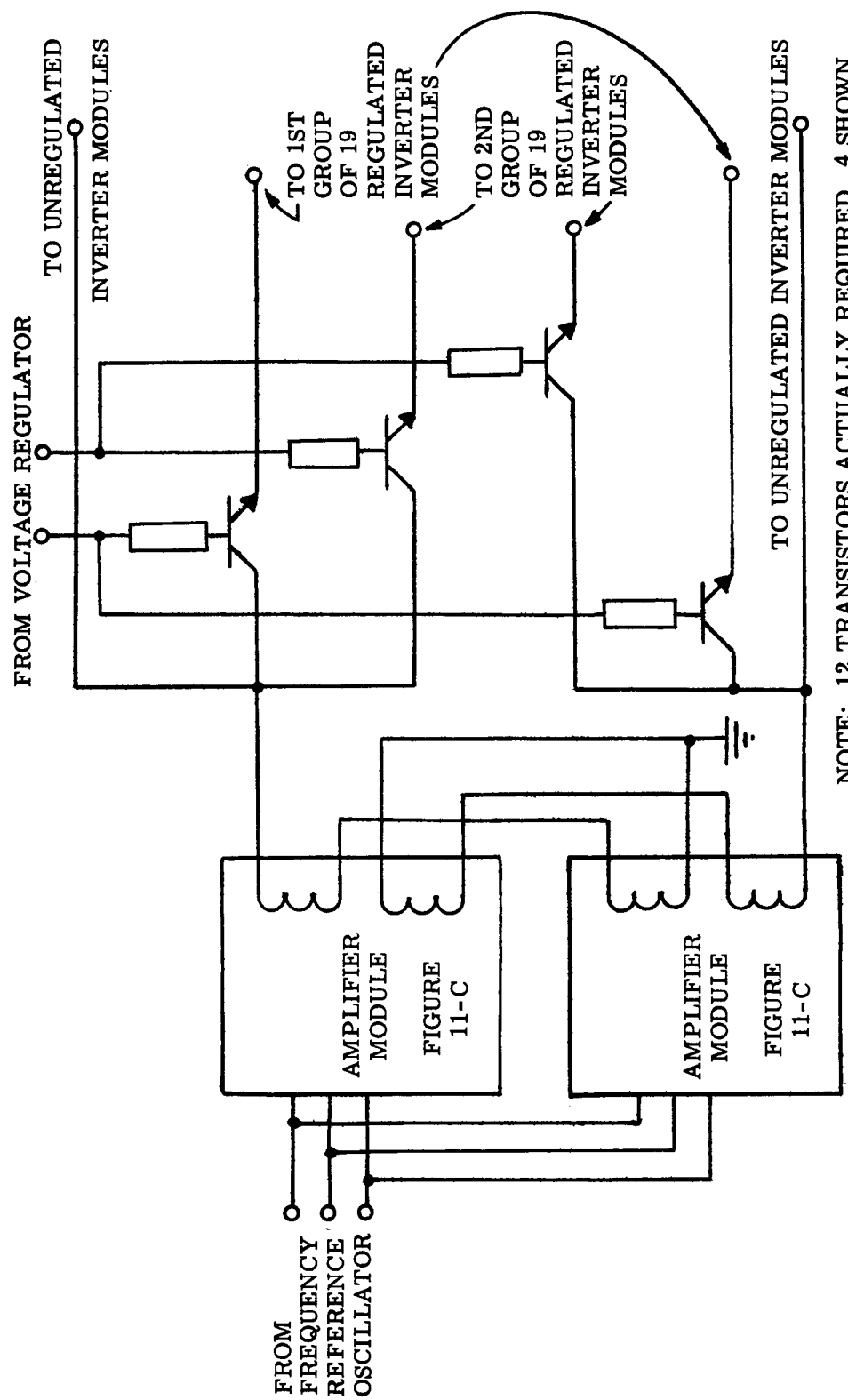


FIGURE 57

Drive Amplifier Schematic Diagram
- 100 Volt 2 Megawatt System

In Figure 57 only two pairs of transistor switches are shown for the sake of clarity. In an actual system four more pairs are required, connected in a similar fashion.

The drive amplifiers for the 0.5-, 1- and 5-megawatt, 100 volt transistor inverters are similar, in principle, to Figure 57. The only differences are the number of amplifier modules and turn-off switches used as shown in Table 37.

300- and 600-Volt Input Systems - The drive for the controlled-rectifier inverters differs from the transistor inverter drives in that no amplifier modules are required. With a 100-volt control bus the transistor frequency reference oscillator delivers the drive power to the inverter directly.

However, the controlled-rectifier inverter modules all require isolated drive sources, and means must be provided for turning off the regulated type inverter modules. The circuits that perform these functions are shown in Figure 58. The transistor-diode switches in the primary circuits of the isolation transformers interrupt the drive to the regulated inverter modules when appropriate signals are received from the voltage regulator. The method of voltage regulation is similar to that described for the transistor converter systems. Table 37 shows the number of isolation transformers and transistor diode switches required for the several different drive amplifiers for controlled rectifier systems.

Design Criteria

Transistor drive amplifiers are used exclusively because they are more easily controlled than silicon controlled rectifier amplifiers. Also, transistors can operate at higher temperatures which simplifies the cooling problem.

The heat loss of the drive amplifier-switching circuits is taken to be equivalent to the heat loss of similar inverter modules operating at 1000 cps. While not strictly accurate for all frequencies, the values are sufficiently accurate, since they represent only a small fraction of the total power converter heat load.

The study of drive amplifiers is based on the following:

1. There is a 100 volt d-c control bus available for all systems except the 20 volt system.
2. The control power for the 20-volt systems comes from the 20 volt power bus.
3. The efficiency of the drive amplifier output transformers is 90 percent.
4. Drive amplifier output transformers are equivalent in size to inverter module transformers of similar power rating.

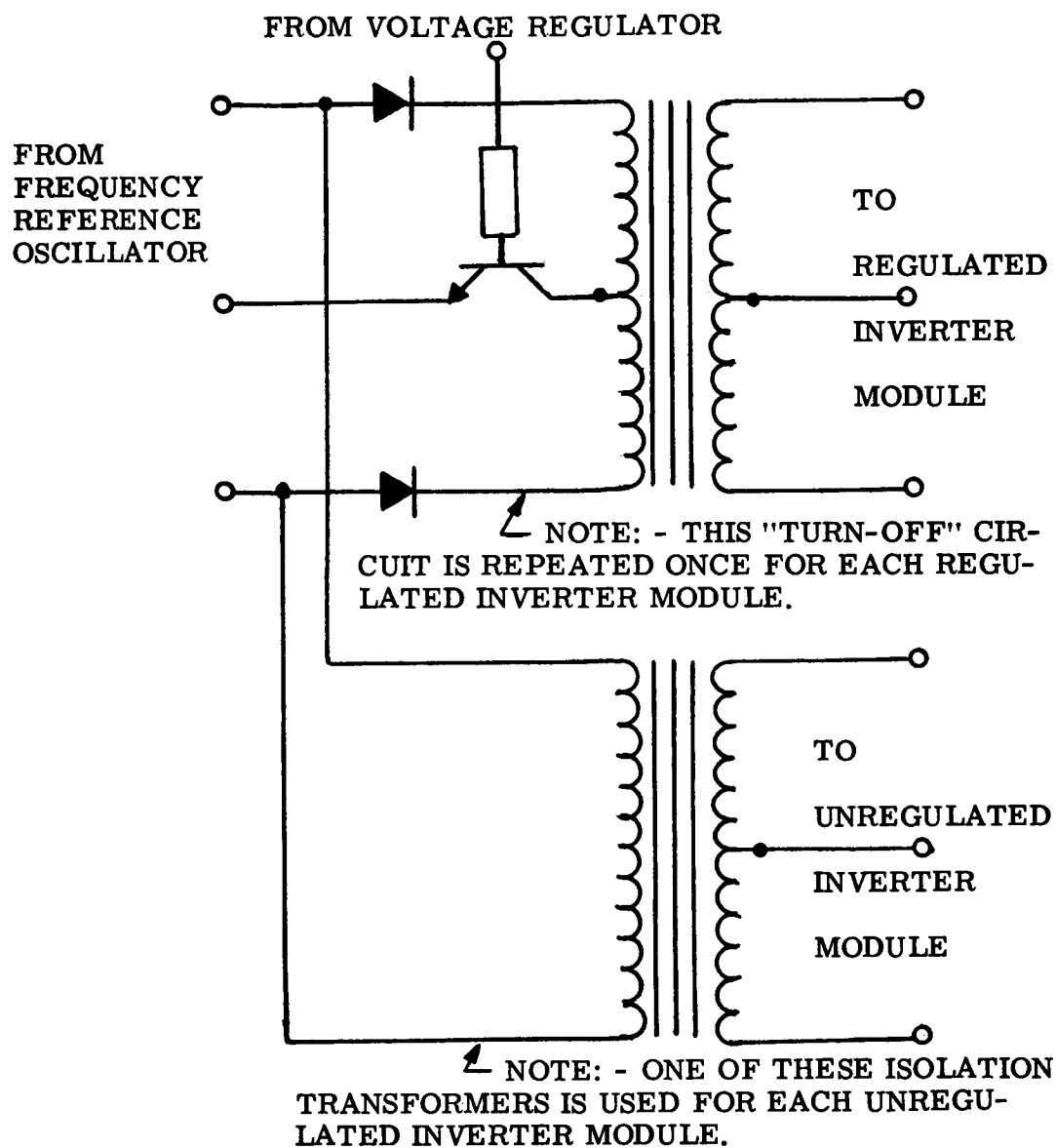


FIGURE 58
Drive Amplifier Schematic Diagram
Typical SCR System

Parametric Data

The electrical parametric data generated for the drive amplifiers are summarized in Table 38. Included in the table are heat loads of the drive amplifiers for the various systems. Curves showing the trend of heat loads vs. system power rating are shown in Figure 59.

Analysis and Interpretations

The drive amplifier forms a physically small, but very important part of the system. The drive amplifiers for the converters using controlled rectifiers are lighter and less complicated than those for the transistor converters. The drive amplifiers for the low voltage transistor systems are required to produce relatively large power outputs and thus are relatively large and heavy.

Recommendations

Further development work on power conditioning equipment having changeable output voltage should be avoided if possible. Size, weight, and complexity of drive amplifiers for the dual-value output voltage systems make these systems undesirable.

Mechanical Design

Description

Mechanical design of the drive amplifiers is based on cold plate cooling with eutectic NaK coolant. In the 20- and 100-volt systems, the drive amplifier modules are similar to the unregulated inverter modules. In these designs, semiconductors are adhesive bonded to insulation, which in turn is adhesive bonded to the cold plate. Adhesive bonding is used to reduce the thermal resistance across the joints in a space environment. Mechanical fastening is used in conjunction with bonding to insure reliability. In the 300- and 600-volt designs, semiconductors are small top hat and glass-bead types with low losses, and are mounted to the cold plate in a manner similar to printed circuit board mounting.

Beryllium oxide insulation is used to provide electric strength and to provide a good thermal path from components to the cold plate. As in the inverter circuits, the insulation thickness for the transistors and commutating diodes, in the 20- and 100-volt designs, is dictated by thermal conduction requirements. Elsewhere, .040-inch insulation is assumed.

Coolant tubes and cold plates are of beryllium to achieve low weight with the required resistance to corrosion by liquid metal. Components are arranged in modules and mounted in rows to the cold plate. In the 20- and 100-volt designs, each row is cooled by two coolant ducts parallel to the row; in the 300- and 600-volt designs, each row is cooled by one duct.

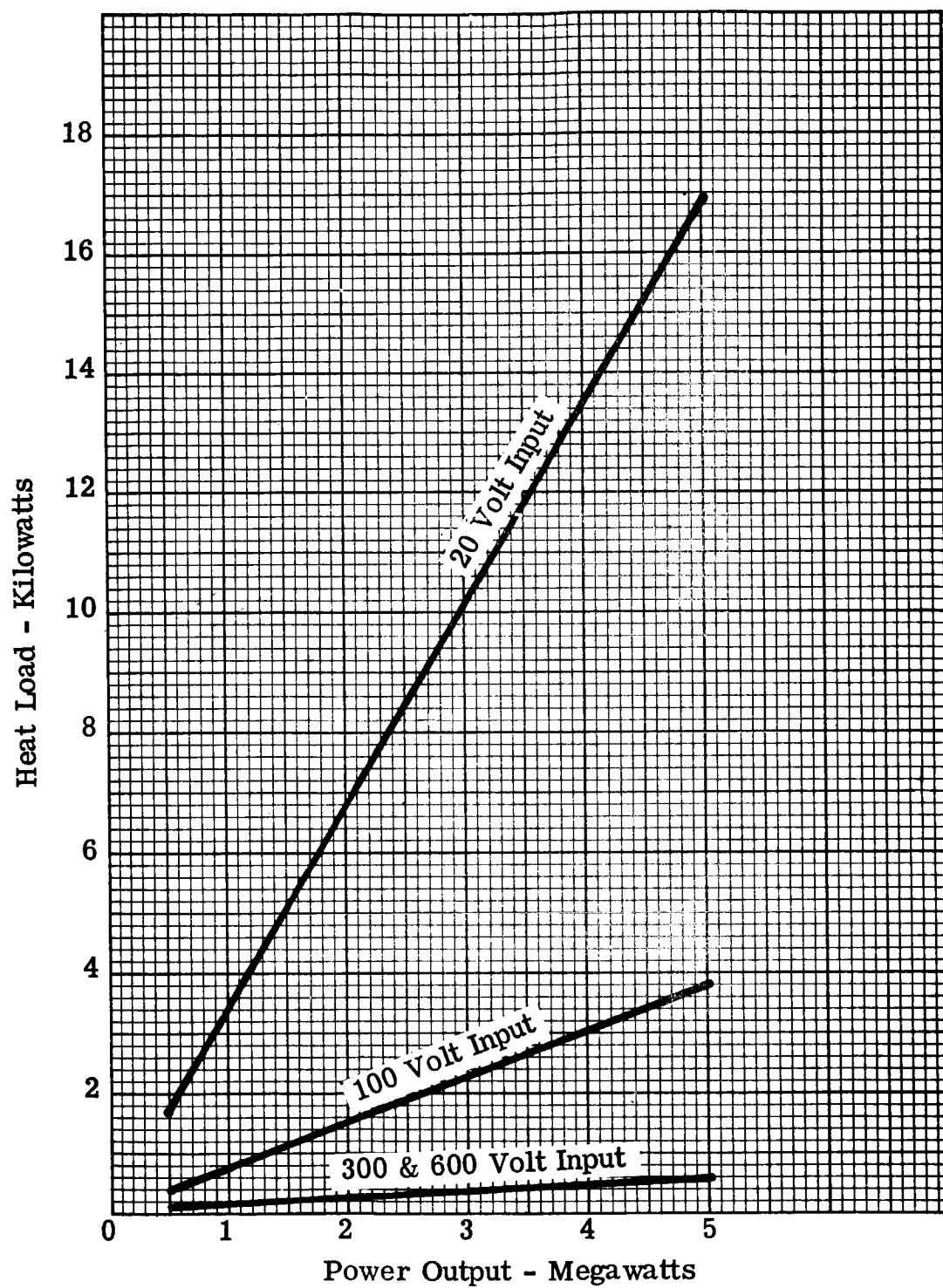


FIGURE 59

Drive Amplifier
Heat Load Vs. Power Output

Design Criteria

The following basic design criteria are used to calculate the required parametric data.

1. The coolant is assumed to be eutectic NaK, which has a specific heat of 0.210 Btu/lbs.-°F, and a density of 0.0306 lbs/in.³. Convection temperature drop is assumed to be 1°C.
2. Beryllium oxide insulation has the following characteristics:

Dielectric Strength	300 volts/mil
Density	0.105 lbs/in.
Thermal Conductivity	100 Btu/hr-ft-°F at 100°C
Thermal Expansion	3.2 x 10 ⁻⁶ in/in/oF from 0 to 200°C 5.0 x 10 ⁻⁶ in.in/oF from 400 to 600°C
3. Beryllium for use in coolant tubes and cold plate has the following characteristics:

Density	0.067 lbs/in. ³
Thermal Conductivity	87 Btu/hr-ft-°F
Thermal Expansion	6.4 x 10 ⁻⁶ in/in/°F
4. Adhesive bonding is .002 inch thick with a thermal conductivity of 0.227 Btu/hr-ft-°F.
5. Minimum achievable thermal resistance between two surfaces not bonded together is 0.2°C/watt in a space environment.
6. In the 20- and 100-volt designs, semiconductor junction temperature is 150°C for transistors, equivalent to 25 percent derating. Case and stud temperature is dictated by thermal resistance and losses for each particular case.
7. In the 300- and 600-volt switching-circuit design, transistors and silicon diodes have a 150°C maximum operating temperature. To maintain these temperatures, the coolant conduit-wall temperature is held to 112°C.
8. Supporting structural weight, not included in the weight of modules, cold plate, insulation, and coolant tube, is 10 percent of the total weight.

Parametric Data

Weights and volumes are given in Table 39 for drive amplifier

TABLE 39

DRIVE AMPLIFIER WEIGHTS AND VOLUMES

Power (megawatts)	0.5	1.0	2.0	5.0
Weights (lbs)				
20 Volts (1000 cps)	195.2	294	588	1469
100 Volts (1000 cps)	48.0	63.5	116.8	360
300 & 600 Volts (all frequencies)	45.6	45.6	93.3	367
Volumes (cu.ft.)				
20 Volts (1000 cps)	3.0	4.62	9.26	23.1
100 Volts (1000 cps)	0.88	1.40	2.65	7.43
300 & 600 Volts (all frequencies)	0.16	0.16	0.16	1.34
Specific Weights (lbs/kw)				
20 Volts (1000 cps)	0.390	0.294	0.294	0.294
100 Volts (1000 cps)	0.096	0.0635	0.0584	0.072
300 & 600 Volts (all frequencies)	0.091	0.0456	0.0467	0.073

designs at input voltages of 20, 100, 300, and 600 volts, and power levels of 0.5, 1.0, 2.0, and 5.0 megawatts. Specific weights are shown in pound per kilowatt. For 20-and 100-volt designs, data is presented for a frequency of 1000 cycles per second. In addition, total weights are given in Table 40 for 20-and 100-volt, one-megawatt designs at frequencies of 50, 100, 400, 1000, 2000, and 5000 cycles per second. At 300 and 600 volts, weight and volume are constant at all frequencies.

Parameters are given in figures 60 and 63. Figure 60 shows drive amplifier total weight as a function of power rating for the four design input voltages at 20 and 100 volts, the weight variation is shown for designs at 1000 cycles per second. Figure 61 shows package volume as a function of power rating.

Variation of drive amplifier weight with frequency is shown in Figure 62 for the 20-and 100-volt, one-megawatt systems. One megawatt was chosen as typical of all power levels. At 300 and 600 volts, there is no weight variation with frequency.

For the 300-and 600-volt, one-megawatt design the required coolant inlet temperature is presented as a function of coolant flow in Figure 63. This curve is derived from the coolant temperature rise curve, Figure 8, with an assumed coolant conduit-wall temperature of 112°C.

Problem Areas

The problem areas anticipated in drive-amplifier designs will be the same as those anticipated for inverter circuits.

Analysis and Recommendations

From comparison of parameters in Table 39, the 300-and 600-volt, one-and two-megawatt designs have the lowest specific weights and the smallest volumes, and thus appear to be most desirable of the designs considered. However, final choice of a design point should depend on consideration of all electrical and mechanical parameters of the complete power system.

Designs for 20-volt systems are much larger and heavier than other designs and should be avoided.

From Figure 62, drive amplifier weight is seen to increase at low frequencies while remaining relatively constant at higher frequencies. This weight trend is due to the drive amplifier transformer.

For the one-megawatt, 20 volt system, frequencies below 1 kilocycle per second should be avoided; for the one-megawatt, 100 volt system, a frequency of 400 cycles per second should be minimum. For the 300-and 600-volt designs, weight is independent of frequency.

From Figure 63, showing variation of coolant inlet temperature

TABLE 40
 DRIVE AMPLIFIER
 WEIGHT VARIATION WITH FREQUENCY
 1 MEGAWATT DESIGN

Frequency, cps	Amplifier Weight (lbs)	
	20 Volt System	100 Volt System
50	1390	270
100	820	162.6
400	382	80.1
1000	294	63.6
2000	257	56.6
5000	222.5	50.1

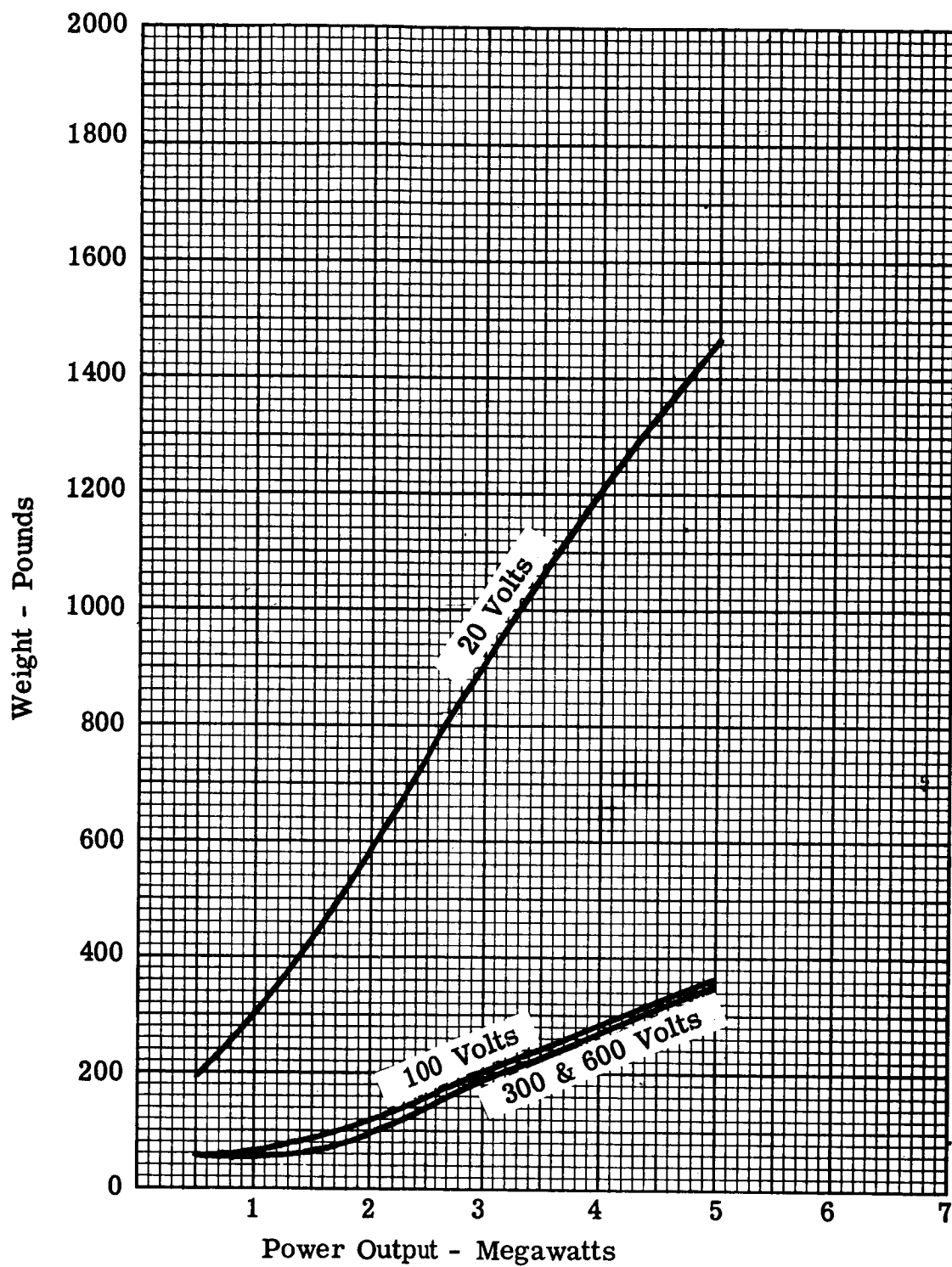


FIGURE 60

Drive Amplifier
Weight Vs. Power Output

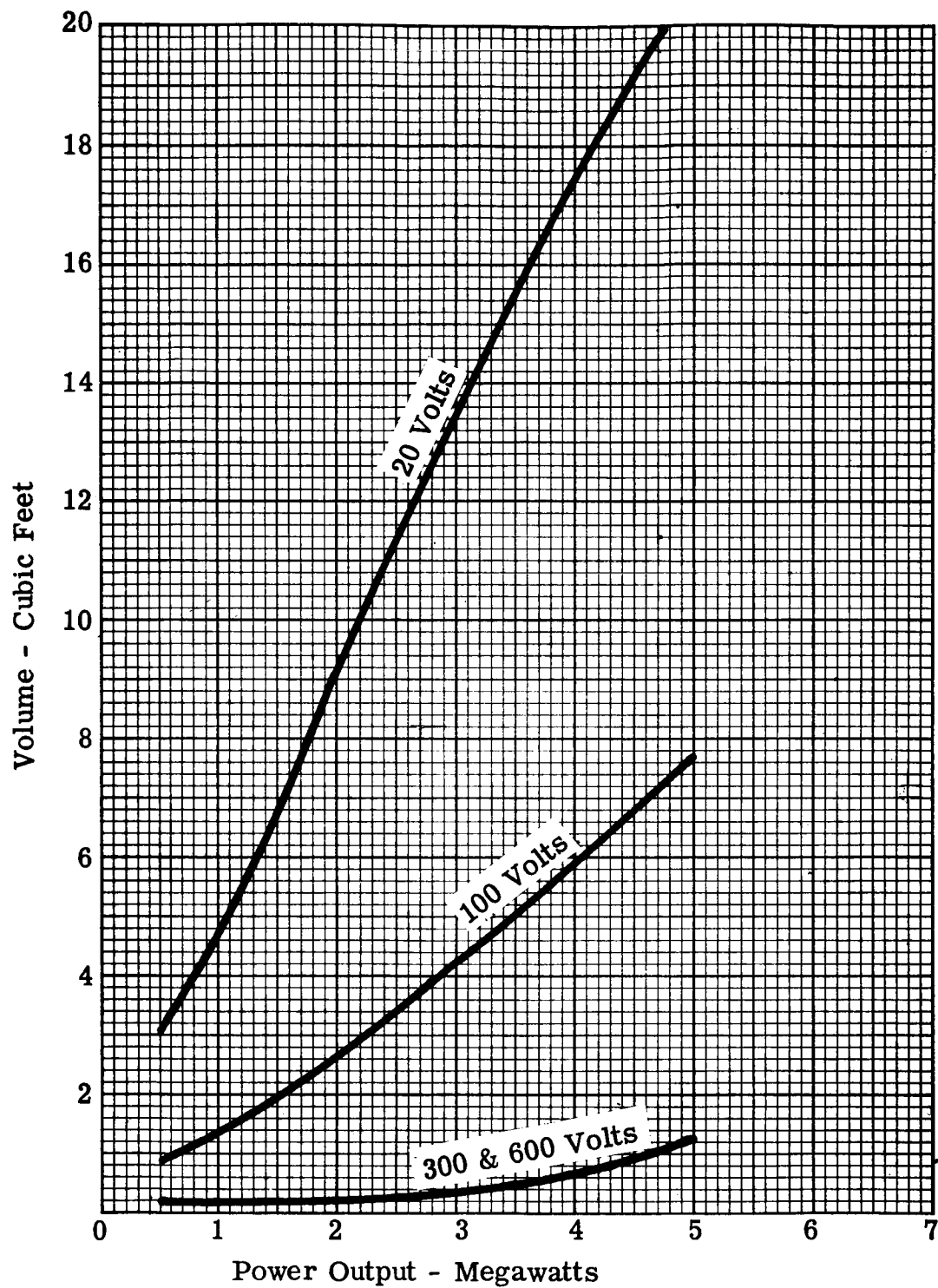


FIGURE 61
Drive Amplifier
Volume Vs. Power Output

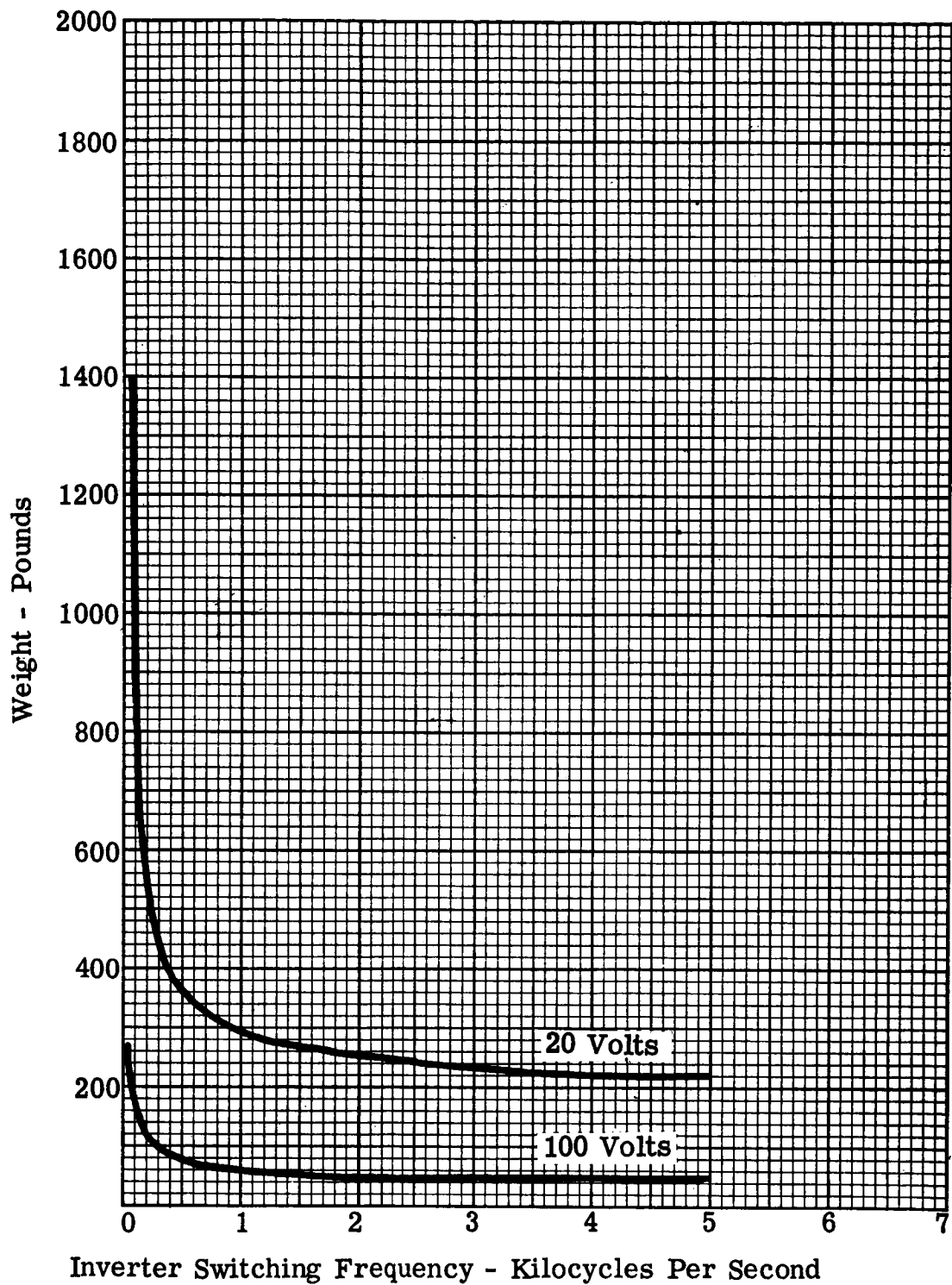


FIGURE 62

Drive Amplifier
Weight Vs. Inverter Switching Frequency

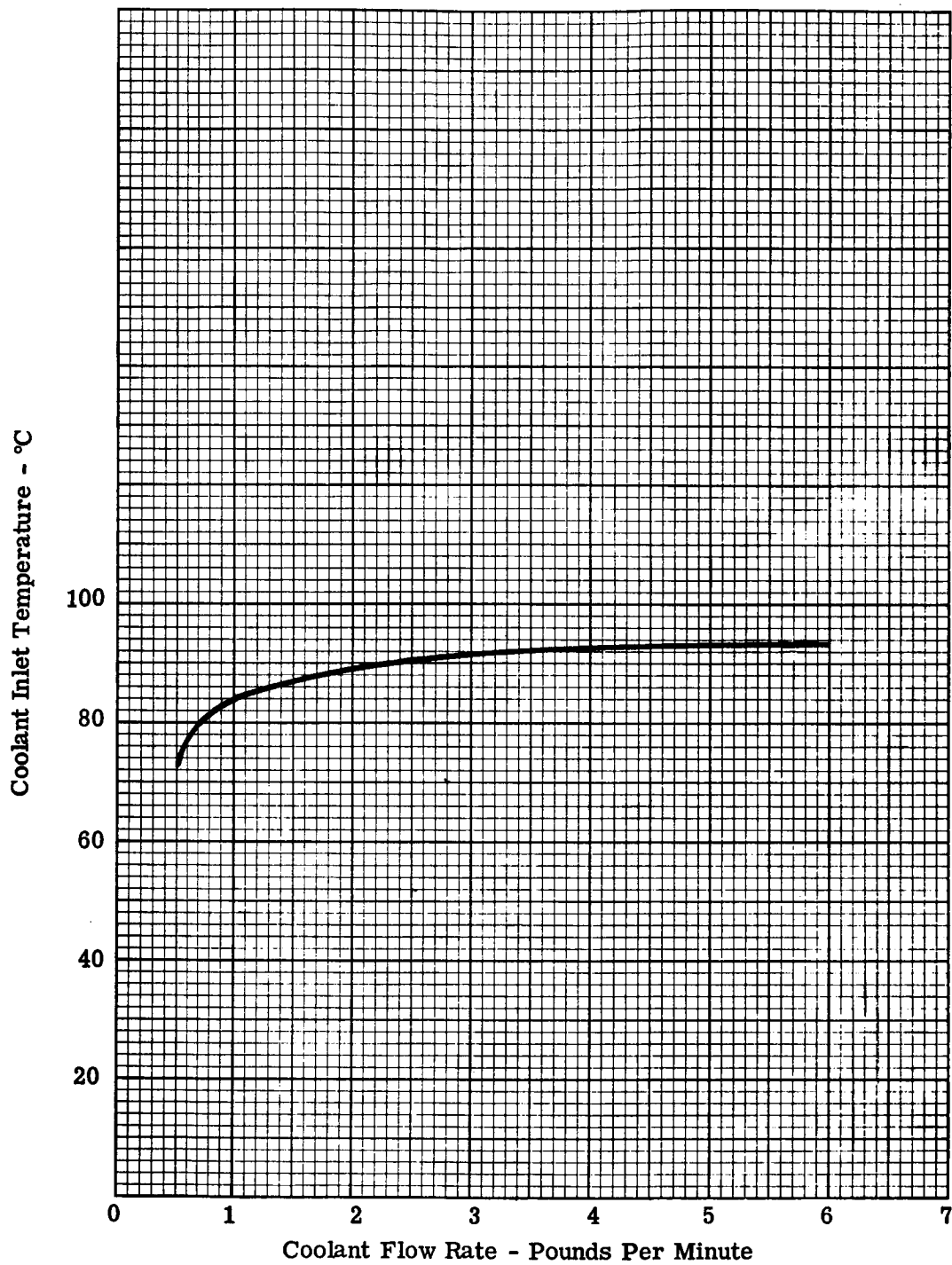


FIGURE 63

Drive Amplifier
1 Megawatt, 300 & 600 Volt Input
Coolant Inlet Temperature Vs. Coolant Flow Rate

with flow rate for the one-megawatt, 300-and 600-volt designs, a coolant flow of one to two pounds per minute is recommended.

The use of beryllium is recommended for coolant tubes and cold plate to achieve a lower weight system.

H. FREQUENCY REFERENCE OSCILLATOR

The function of the frequency-reference oscillator is to determine the operating frequency of the power-conversion equipment. It is not a constant-frequency device. Rather, its frequency varies in direct proportion to its input voltage. Since the oscillator obtains its input voltage from either the main d-c input bus, or a tap whose voltage is some constant fraction of the main bus voltage, the oscillator output frequency is proportional to the main-bus voltage. This varying frequency is desirable because it prevents saturation of the power transformers in case of a higher than nominal input voltage. The nominal or full-load frequency of the power conversion system is fixed by the design of the frequency reference oscillator. While the system is operating, the nominal frequency is maintained as long as the nominal input voltage is maintained.

Electrical Design

Figure 64 represents the circuit of the frequency reference oscillator. The basic elements are the saturable transformer and the two transistors, Q1 and Q2. Transistors Q3 and Q4 have been added to stop the oscillator when required. The other circuit elements are needed to assure reliable starting and to protect the transistors from excessive voltage and currents.

Operation

The operation of this circuit has been thoroughly described in the literature. Briefly, it is as follows. When power is applied, one of the main transistors starts to turn on. Its collector current, flowing through the transformer, induces a voltage in the feedback winding which drives the transistor into full conduction. This state continues until the transformer saturates, whereupon the other transistor starts to conduct and the first one turns off.

The result is a square wave a-c output which feeds the drive amplifier, and causes the inverter stages to switch in synchronism with the oscillator.

Design Criteria

The following assumptions were used in the study of frequency reference oscillators.

1. The oscillator receives power from the main d-c input bus in the 20-and 100-volt input power conversion systems.
2. The oscillator receives power from a tap on the main power supply in the 300-and 600-volt input systems. The tap voltage is 100 volts, nominal, and is either $1/3$ or $1/6$ of the actual main bus voltage at all times.

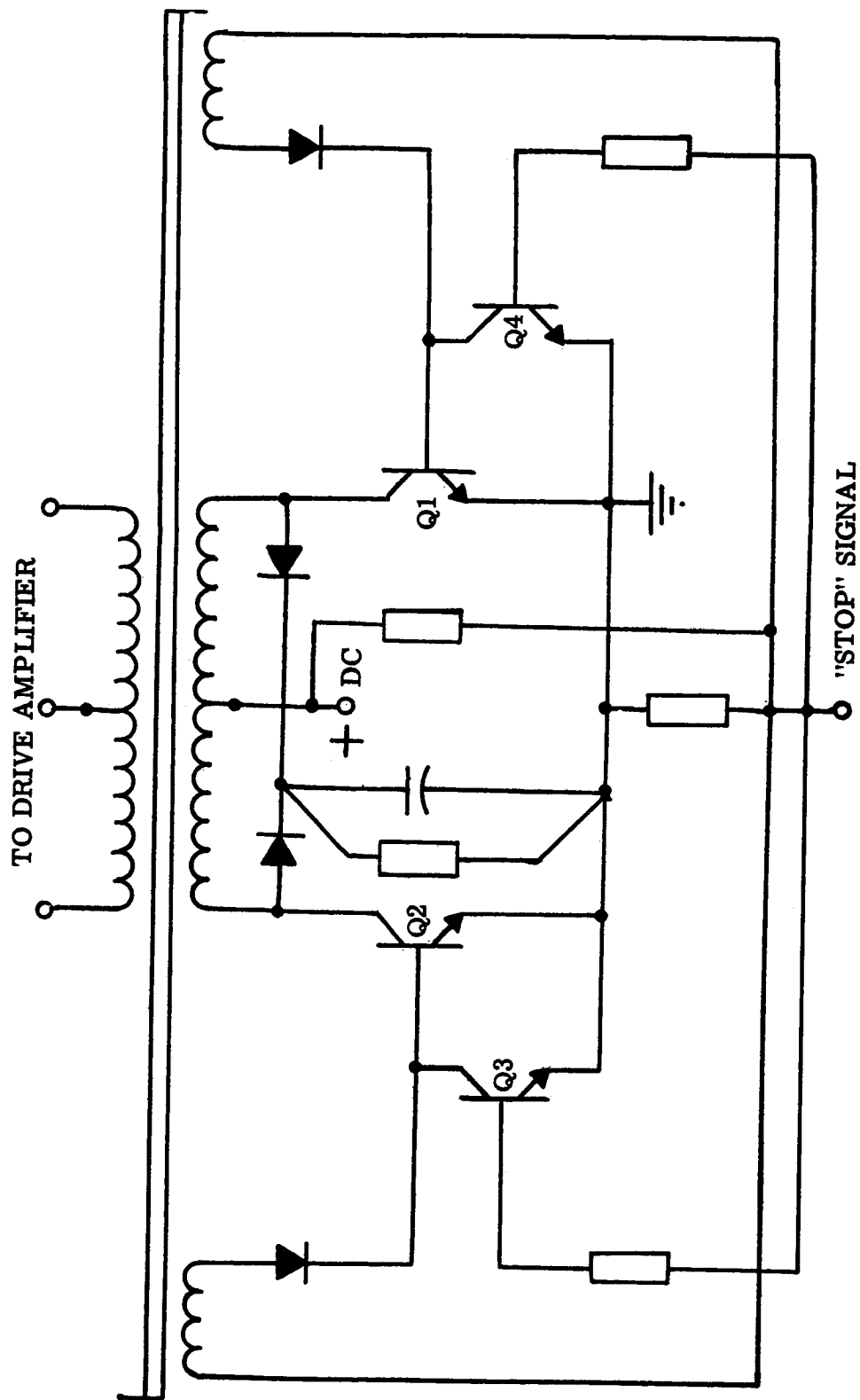


FIGURE 64
Frequency Reference Oscillator
Schematic Diagram

In all designs the main transistors are the same as those used in the inverter power stages. All transformers use toroidal cores of Orthonol material. All other parts are currently available types. The two extremes of frequency, 50 and 5000 cycles per second, were used to calculate two transformer weights and two heat loss figures for each oscillator. The power output requirements of the oscillators for the various systems were determined by the input requirements of the corresponding drive amplifiers.

Parametric Data

Table 41 summarizes the electrical parametric data for the frequency reference oscillator. It is noticed that only the two extremes of frequency are shown, 50 and 5000 cps. The values for a practical system will fall somewhere between these extremes. Because the frequency-reference oscillator represents a very small portion of the total weight and losses of the system, it was felt that a complete frequency scan was not justified.

The two curves of Figure 65 show the maximum and minimum values of oscillator heat loads. Neither the maximum nor the minimum correlates with any particular system input voltage or frequency. An actual plot of the many different oscillator designs results in a scattering of points, of which the curves shown are the outlines. Hence the only safe assumption is that all oscillator designs will fall within the range shown. The reason for the extreme variability of designs is that, for minimum weight, the oscillator must be tailored precisely to the requirements of the drive amplifier, which in turn are highly variable, depending on input voltage, power rating, number of stages of amplification and switching frequency.

Analysis and Conclusions

The frequency reference oscillator is physically small, and has relatively low heat losses. Since it weighs only a few pounds, it is expected to be only a minor factor in determining the optimum power conversion system.

No particular problems are anticipated with this functional block. Suitable materials and components are presently available and the design techniques have been fully verified.

Mechanical Design

The frequency reference oscillator, voltage regulator and current protection circuit are similar in mechanical design requirements and are designed to be included in a single package. The package is designed for cold plate cooling, with the coolant flow and inlet temperature based on the cooling requirements of the voltage-regulator components, which have the lowest required temperature.

TABLE 41

FREQUENCY REFERENCE OSCILLATOR ELECTRICAL PARAMETERS

System Input Voltage	20	20	20	20	100	100	100	300	300	300
System Power (watts)	.5	1	2	5	.5,1	2	5	.5,1	2	5
Oscillator Power Output (megawatts)	300	480	40	60	20	40	100	150	300	1200
Oscillator Transformer										
Weight (lbs)	15	23	6.0	6.9	3.75	6.0	8.3	10	15	36
50 cps	.9	1.4	.2	.3	.12	.2	.5	.7	.9	2.75
5000 cps										
Losses										
50 cps	39	72	15	22	6.4	15	18	20	39	122
5000 cps	9	17	3.5	5	1.5	3.5	4.5	5	9	24
Transistor Losses										
Base Drive (watts)	10	20	.2	.3	.2	.2	.6	1	2	10
Collector (watts)	15	24	.4	.5	.2	.4	1.0	1.5	3	12
Total Electrical Weight (lbs)										
50 cps	16.2	24.2	7.2	8.1	5.0	7.2	9.5	11.2	16.2	37.2
5000 cps	2.1	2.6	1.4	1.5	1.3	1.4	1.7	1.9	2.1	4.0
Total Losses (watts)										
50 cps	64	116	16	23	7	16	20	23	44	144
5000 cps	34	61	4	6	2	4	6	8	14	46

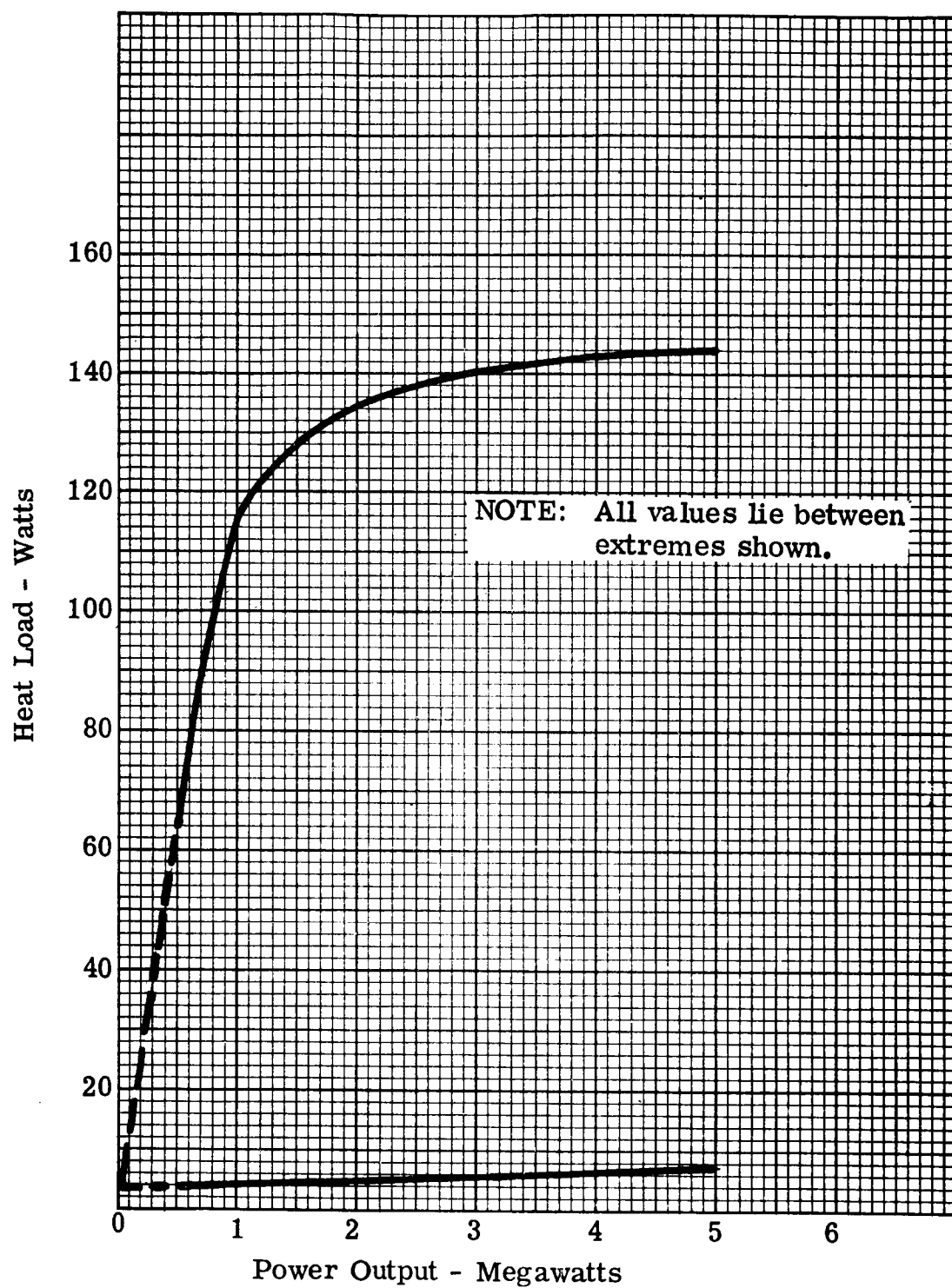


FIGURE 65
Frequency Reference Oscillator
Heat Load Vs. Power Output

Single package design for the three circuits is utilized to achieve a low weight design. The individual circuits vary in weight from 2.75 to 25.4 pounds. In this range, the required percentage of structural weight increases as the total package weight is reduced. Thus, to keep structural weight at a minimum, it is desirable to combine the units in a larger package.

Weight and volume are presented in this section for the frequency reference oscillator circuit, and for the entire package.

Description

Frequency reference oscillator mechanical design is based on cold plate cooling with eutectic NaK coolant. Semiconductors are adhesive bonded to beryllium oxide insulation, which in turn is adhesive bonded to the cold plate. Adhesive bonding is used to reduce the thermal resistance across the joints in a space environment. Mechanical fastening is used in conjunction with bonding to insure structural reliability. Beryllium oxide insulation is used to provide dielectric strength and to provide a good thermal path from components to the cold plate.

Resistors, contained in insulated cases, are bonded and mechanically fastened directly to the cold plate. The transformer is potted and bonded to the cold plate to facilitate cooling.

Coolant tubes and cold plate are of beryllium to achieve low weight with the required resistance to corrosion by liquid metal.

Design Criteria

The following basic design criteria are used to calculate the required parametric data.

1. The coolant was assumed to be eutectic NaK, which has a specific heat of 0.210 Btu/lb-°F, and a density of 0.0306 lbs./in.³. Convection temperature drop was assumed to be 1°C.
2. Beryllium oxide insulation has the following characteristics:

Dielectric Strength	300 volts/mil
Density	0.105 lbs/in. ³
Thermal Conductivity	100 Btu/hr-ft-°F at 100°C
Thermal Expansion	3.2 x 10 ⁻⁶ in/in/°F from 0 to 200°C 5.0 x 10 ⁻⁶ in/in/°F from 400 to 600°C

3. Beryllium for use in coolant tubes and cold plate has the following characteristics:

Density	0.067 lbs/in. ²
Thermal Conductivity	87 Btu/hr-ft-°F
Thermal Expansion	6.4×10^{-6} in/in/°F

4. Adhesive bonding is .002 inch thick, with a thermal conductivity of 0.227 Btu/hr-ft-°F.
5. Minimum achievable thermal resistance between two surfaces not bonded together is 0.2°C/watt in a space environment.
6. Semiconductor device stud or case temperatures are 140°C for all designs. This is equivalent to at least 25 percent derating of the device junction temperatures.
7. Supporting structure weight, not included in the weight of cold plate, insulation, and coolant tube, varies from 20 to 22.5 percent of the total weight, dependent on the combined package weight of the oscillator, voltage regulator, and current protection circuit.

Parametric Data

Frequency reference oscillator weights and volumes are presented in Table 42 for all designs at input frequencies of 50 and 5000 cycles per second. These frequency extremes are chosen to show an envelope of parametric data.

Figure 66 shows variation of coolant inlet-temperature with flow rate for the common cold plate on which the oscillator, voltage regulator, and current-protection circuit are mounted. The curve is based on maintaining a cold-plate temperature of 105°C in the voltage-regulator portion with losses from the two-megawatt voltage regulator design. The coolant flow required for this voltage regulator is sufficient to maintain oscillator semiconductor case temperatures below the 140°C allowable maximum.

The weights and volumes for the complete package, containing oscillator, voltage regulator and current protection circuits, are presented in Table 43. Because these parameters do not depend directly on system power rating or input voltage, meaningful curves can not be plotted. The required data for a system design may be found in the tables.

Problem Areas

Problem areas anticipated in frequency-reference oscillator design are the same as discussed previously in the output filter,

TABLE 42

FREQUENCY REFERENCE OSCILLATOR

WEIGHTS AND VOLUMES

	20	20	20	20	100	100	100	100	300 & 600	300 & 600	300 & 600
System Voltage (volts)	20	20	20	20	100	100	100	100	300 & 600	300 & 600	300 & 600
System Power (megawatts)	0.5	1.0	2.0	5.0	0.5	1.0	2.0	5.0	0.5	1.0	2.0 5.0
Weight (lbs)											
50 cps	21.6	31.6	10.13	11.12	7.35	7.35	10.13	13.07	15.5	15.5	21.6 48.0
5000 cps	4.05	4.69	2.82	2.92	2.75	2.75	2.82	3.12	3.79	3.79	4.02 6.42
Volumes (cu.ft.)											
50 cps	0.380	0.380	0.191	0.191	0.191	0.191	0.191	0.191	0/380	0.380	0.380 0.500
5000 cps	0.112	0.112	0.107	0.107	0.107	0.107	0.107	0.107	0.112	0.112	0.112 0.168

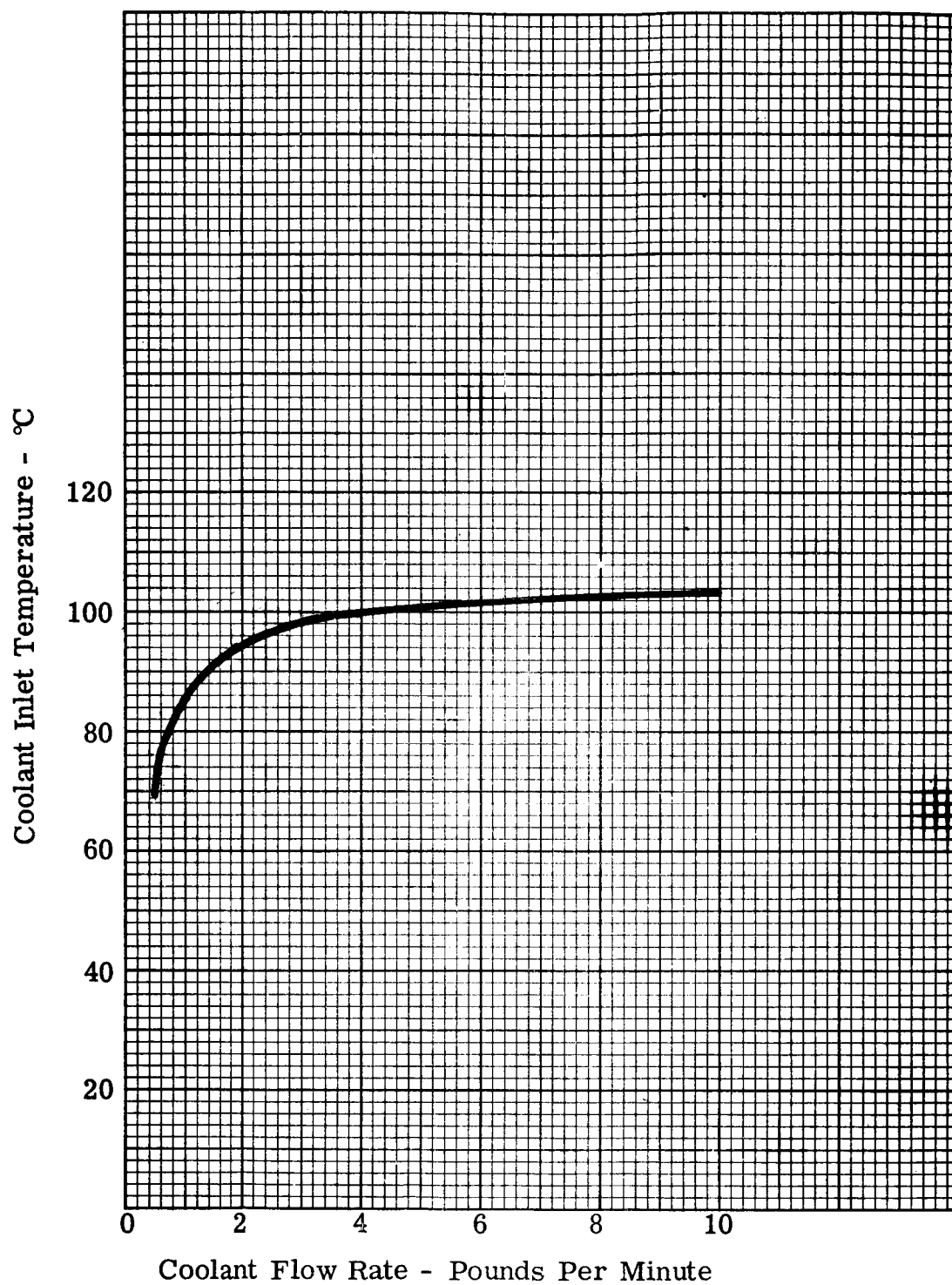


FIGURE 66

Frequency Reference Oscillator, Voltage Regulator, Current
Protection Circuit Package
Coolant Inlet Temperature Vs. Coolant Flow Rate

TABLE 43

TOTAL WEIGHTS AND VOLUMES OF PACKAGE COMPRISING
FREQUENCY REFERENCE OSCILLATOR, VOLTAGE REGULATOR AND
CURRENT PROTECTION CIRCUIT

	20	20	20	20	100	100	100	100	300 & 600	300 & 600	300 & 600	300 & 600
System Voltage (volts)	20	20	20	20	100	100	100	100	300 & 600	300 & 600	300 & 600	300 & 600
System Power (megawatts)	.5	1	2	5	.5	1	2	5	.5	1	2	5
Weights (lbs)												
50 cps	45.9	45.9	37.96	58.4	32.1	32.1	37.9	60.3	40.1	40.1	49.0	95.
5000 cps	28.9	29.6	30.78	50.2	27.8	27.8	30.7	50.4	28.7	28.7	31.9	53.7
Volumes (cu.ft.)												
50 cps	0.89	0.89	0.84	0.79	0.70	0.70	0.84	0.83	0.89	0.89	1.03	1.14
5000 cps	0.62	0.62	0.75	0.71	0.62	0.62	0.75	0.75	0.62	0.62	0.76	0.81

inverter circuit, and other portions of this report. Briefly, they are

1. Development of techniques for use of beryllium
2. Development of reliable adhesive bonds.

Analysis and Recommendations

Choice of a design point depends on consideration of all of the electrical and mechanical parameters of a complete power system, of which the frequency reference oscillator is a relatively small part in size and weight. Thus, the optimum mechanical design choice of oscillator is expected to have a negligible effect on the final choice of system.

As noted in Table 42, weight and size decrease with increased frequency. Coolant parameters are determined by voltage regulator requirements. Figure 66 shows variation of coolant inlet-temperature with flow rate, from which a flow rate of two pounds per minute is recommended for the two-megawatt design.

J. VOLTAGE REGULATOR

The function of the voltage regulator is to maintain the output voltage of the d-c to d-c converter at its rated value within a tolerance of ± 5 percent. As previously explained, the method of regulation is to activate or de-activate certain power inverter modules to add or subtract increments of voltage from the output. These particular inverter modules have been called "regulated" inverter modules. They are de-activated by means of solid state turn-off switches located in the drive amplifier. The voltage regulator responds to deviations of output voltage and signals the drive amplifier to turn on or off the proper number of regulated inverter modules to maintain the output at the rated value.

Electrical Design

Description

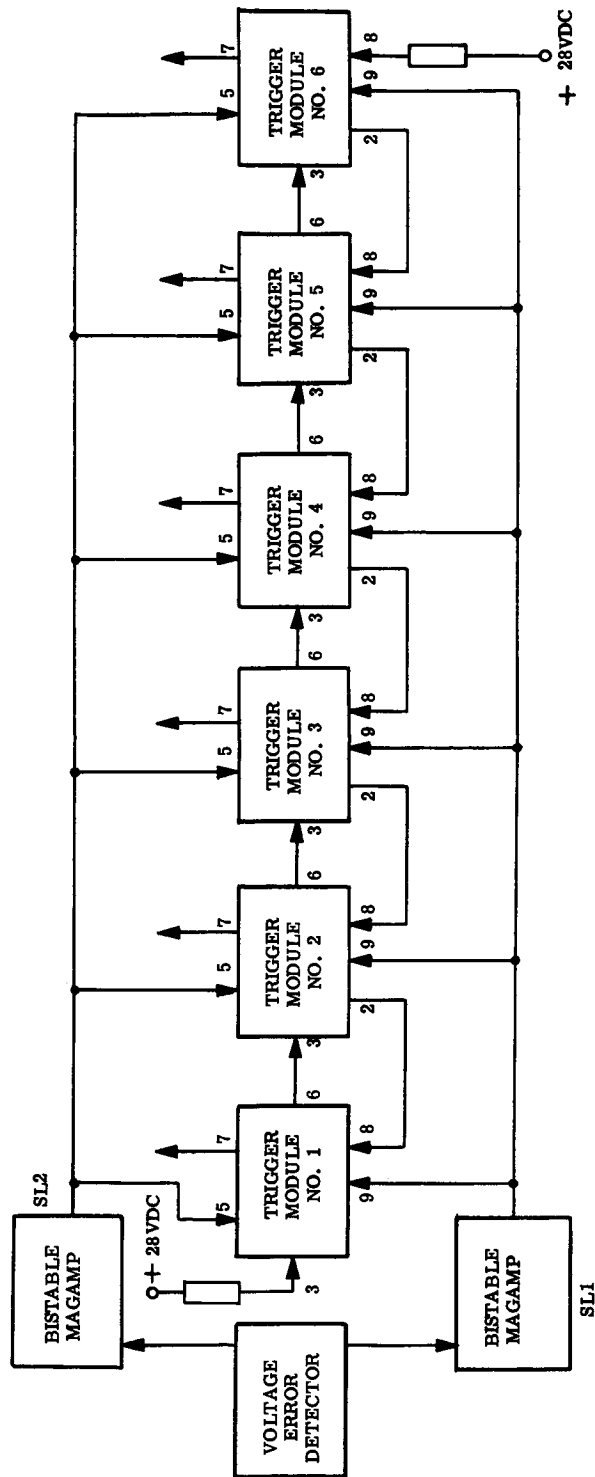
The simplest regulator is the one capable of controlling 6 regulated inverter modules or 6 groups of modules. This type of regulator is suitable for all the converters studied, except the 5-megawatt units.

The regulator consists of the following parts:

1. One error-detector circuit, which senses the deviations of output voltage and produces signals whenever the output voltage exceeds the ± 5 percent tolerance.
2. Two bistable magnetic amplifiers which amplify the signals emitted by the error detector. Output from one magnetic amplifier represents higher than normal voltage; the other represents lower than normal output voltage.
3. Six trigger modules corresponding to the six regulated-inverter modules. These form a reversible counter, sensitive to signals from the magnetic amplifiers. The "on" condition of a trigger circuit causes its corresponding regulated inverter module to be turned "on".
4. One Zener-diode clamp, connected across a portion of the thermionic power source to provide a constant control bus voltage for the trigger circuits and magnetic amplifier bias circuits.

The interconnection of these various circuits to form a six-stage regulator, is shown in Figure 67. Arrows represent the direction of signal flow.

The circuits themselves are shown in Figures 68, 69, 70 and 71. The operation of each circuit, as well as that of the entire regulator, is described below.



NOTE: TERMINALS 7 CONNECT TO
DRIVE AMPLIFIER

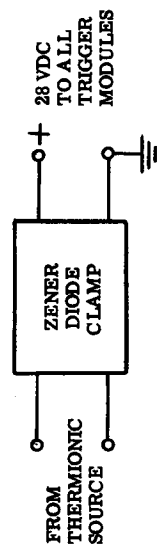


FIGURE 87

Voltage Regulator Functional Diagram

*AUXILIARY CONTACT
ON SWITCHGEAR -
USED ONLY FOR 5
MEGAWATT SYSTEMS

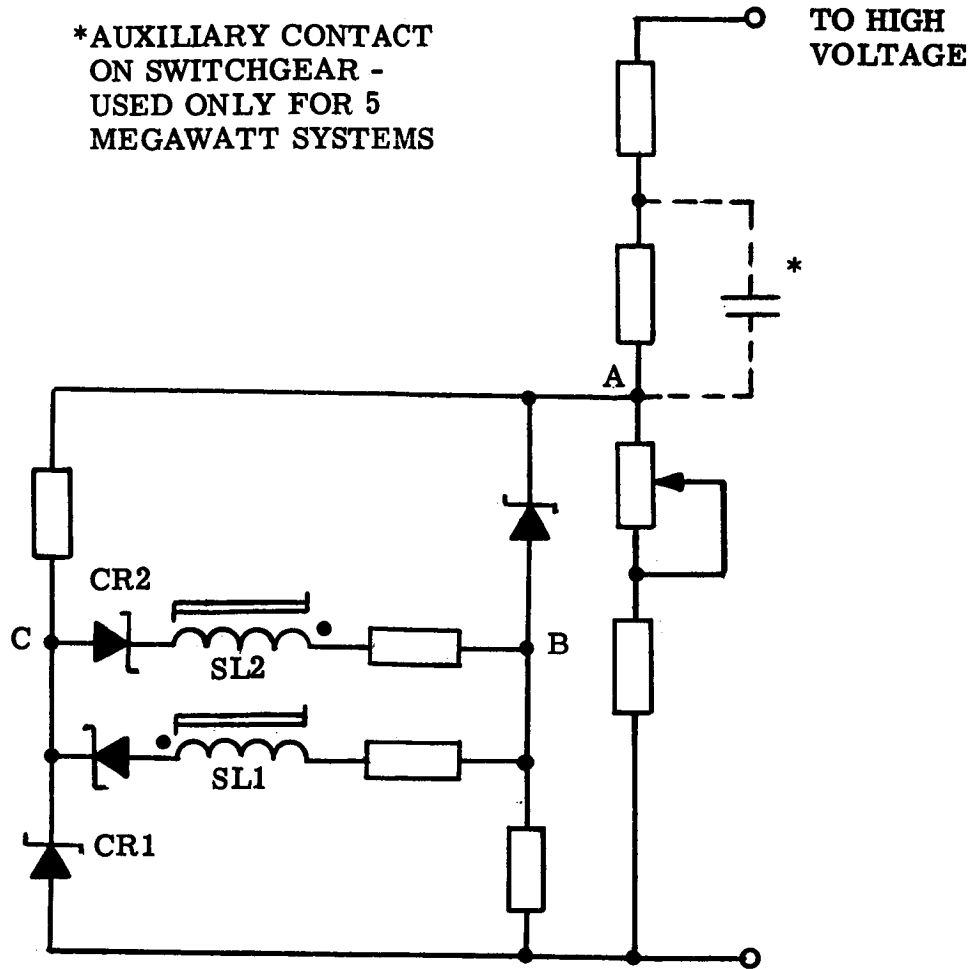


FIGURE 68
Voltage Regulator
Error Detector Schematic Diagram

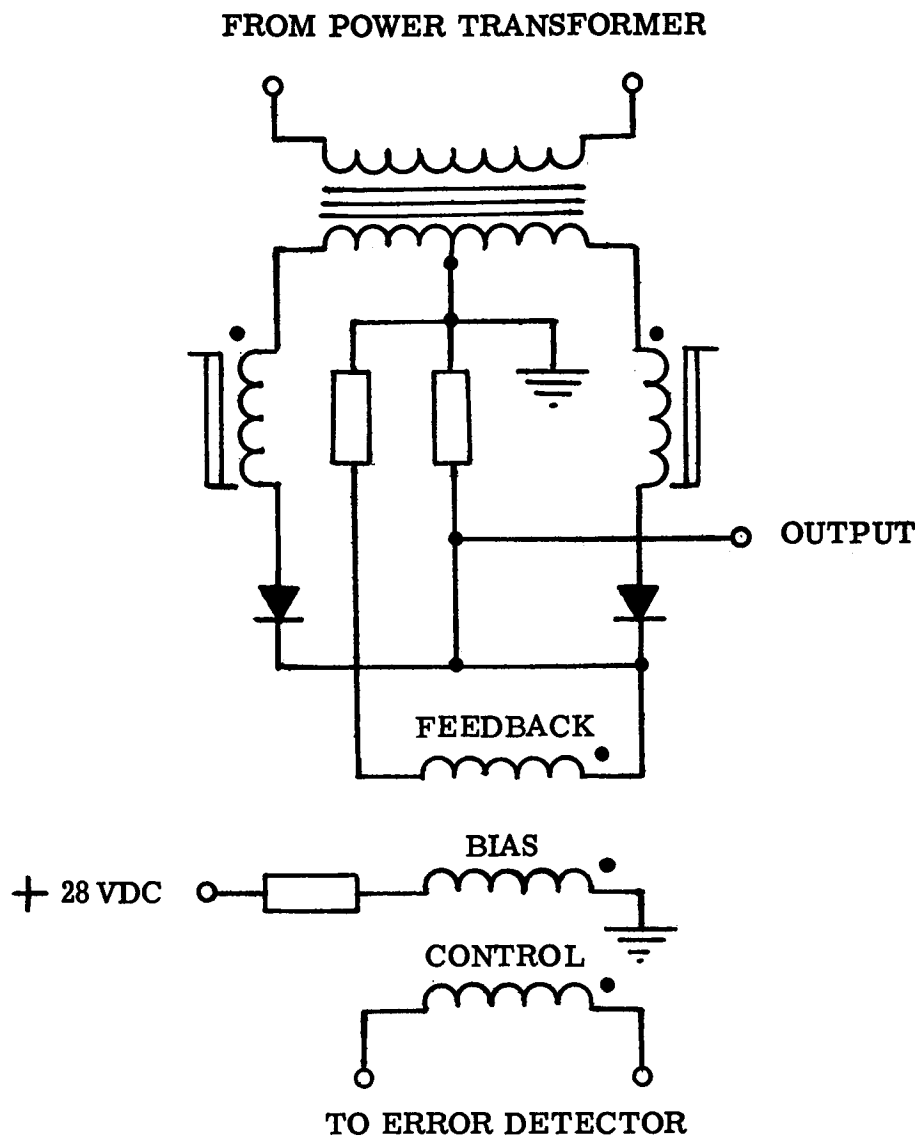


FIGURE 69
Bistable Magnetic Amplifier Schematic Diagram



FIGURE 70
Trigger Module Schematic Diagram

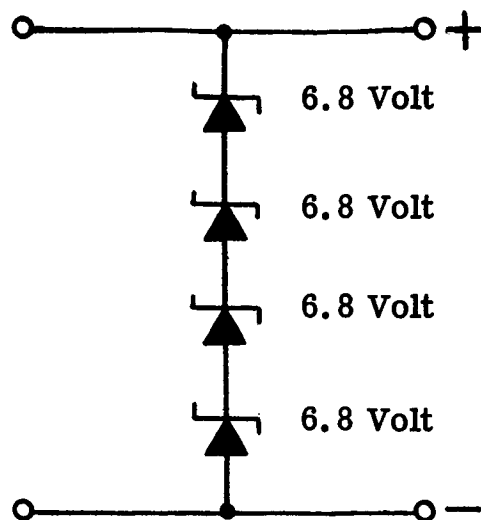


FIGURE 71
Zener Diode Clamp Schematic Diagram

Operation

The operation of the voltage regulator is described, assuming the following initial conditions.

1. The output voltage is normal.
2. All the regulated inverter modules are on. Therefore, all trigger modules are on and both magnetic amplifiers are off.

Assume that the output voltage begins to rise; e.g., because of a reduction of load. Refer to Figure 68. The rising output voltage causes the voltage at point A to rise, which in turn causes an equal rise at B. However, the voltage at C is fixed by the Zener diode CR1. When the voltage difference between B and C has risen enough to break down Zener diode CR2 which corresponds to a (+)5% rise above normal output voltage, current passes through the control winding of magnetic amplifier SL2, shown in Figure 69.

Until this time, both bistable magnetic amplifiers are off. The control current is in the direction to turn off SL1 and to turn on SL2. Therefore, SL1 stays off, but SL2 starts to turn on. Regenerative action of the feedback winding on SL2 causes it to turn on and lock in the full on condition.

The magnetic amplifier output voltage is applied to terminal 5 of all the trigger modules (Figure 70). The signal is in a direction to turn off the trigger modules, but is of insufficient magnitude by itself. Off condition of the trigger is represented by Q1 conducting; Q2 not conducting. Because of the initial conditions assumed above, all trigger modules are initially on, with Q2 conducting. However, there is an additional input to trigger module number 1, via terminal 3. The sum of this input plus the magnetic amplifier signal is sufficient to break down CR1 and cause Q1 to start conducting. This in turn removes base drives from Q2, so that it stops conducting and the module turns off. When Q2 stops conducting, the voltage at its collector rises, turning on Q3 which in turn causes Q4 to turn on. Transistor Q4 shorts terminal 7 to ground. This signal is fed to the drive amplifier, causing one of the regulated inverter modules to be turned off.

Meanwhile, capacitor C1 has been charging through resistor R1 of the time delay circuit. If the d-c output voltage remains above normal, the signal from magnetic amplifier SL2, added to the voltage across C1, becomes sufficient to break down Zener diode CR1 in the next trigger module. Hence, the second trigger module turns off, turning off the second inverter module.

This process continues until the output voltage is returned to a value slightly below normal, whereupon the current reverses through SL2 control winding, turning off the magnetic amplifier.

The trigger modules that are off remain off, and the entire system runs in a steady state until the next disturbance occurs.

When the output voltage falls below the (-) 5 percent tolerance limit, the regulator acts in the opposite direction, restoring regulated modules to operation. In this case magnetic amplifier SL1 turns on, feeding a signal to terminal 9 of the trigger modules. The last module to turn off is forced back on, Q2 conducts, Q1 stops conducting, and Q5 supplies a delayed signal to the next module. In this way a "turn-on" signal is propagated back down the line of trigger modules until the output voltage has been returned to normal.

The voltage regulators for the 5-megawatt, dual-output voltage converters function in a manner similar to the units just described. The major differences are that there are seven stages of regulation (7 trigger modules), and the error-detector circuit must be modified to enable it to operate at two different voltages.

When operating at low output voltage, an auxiliary contact, part of the rectifier-bank switchgear, short circuits a portion of the voltage divider in the error-detector circuit. See Figure 68. This causes the power converter to seek a 600-volt output, consistent with having the power rectifiers connected in parallel.

When operating at high output voltage, the switchgear connects the power rectifiers in series; the auxiliary contact opens, setting the regulator for 5000 volts.

Design Criteria

The assumption was made that a 28-volt control bus is available from the thermionic source. This bus should be capable of approximately 150 watts output at 28 volts. The voltage is maintained by a Zener-diode clamp across the bus, as explained previously.

The major design criteria for the regulator are set by the method of voltage regulation and the drive amplifier signal requirements, both of which are determined earlier in the study.

Maximum use of digital-type circuits was decided upon in the interests of simplified design and best reliability. The circuits chosen should tolerate very wide variations in component parameters, without degradation of performance.

Parametric Data

The electrical parametric data for the voltage regulator was shown in Table 44.

The fact that there is more heat loss generated than d-c power supplied may appear strange until it is realized that much of

TABLE 44

VOLTAGE REGULATOR ELECTRICAL PARAMETERS

Output Voltage	5kv	20 kv	0.6 or 5 kv
System Rating	500, 1000 kw	2000 kw	5000 kw
Number of Trigger Modules	6	6	7
Heat Loss per Module (watts)	20	20	20
Number of Bistable Magnetic Amplifiers	2	2	2
Heat Loss per Bistable (watts)	16	16	16
Number of Error Detectors	1	1	1
Heat Loss per Detector (watts)	272	1022	272 at 5 kv 55 at 600 v
Number of Zener Diode Clamps	1	1	1
Heat Loss per Diode (watts)	40	40	40
Total Heat Loss (watts)	464	1214	484 at 5 kv 267 at 600 v
28 Volt D-C Power Input Required (watts)	150	150	170

the power required to run the regulator comes from points within the power conversion system. Specifically, the magnetic amplifiers get their power from taps on the power transformers and the error detectors get their power from the d-c output bus. The voltage-divider resistors used in the error detectors are responsible for the largest portion of the total heat loss.

Recommendations

The technique of voltage regulation is novel and untried. While it appears to be feasible, experimental verification if necessary before planning to use it in an actual piece of flight hardware. The experimental approach would uncover any unforeseen problems and allow any necessary modifications to be made.

Further, it is recommended that a spare regulator be added to the system with means for changeover in case the first regulator should fail. The increase in reliability should more than offset the additional weight.

Mechanical Design

The frequency-reference oscillator, voltage regulator, and current-protection circuit are combined in a single package. The portion of the total package weight and volume that is attributed to the voltage regulator is presented here.

Description

The construction is described previously in the mechanical discussion for the frequency reference oscillators.

Design Criteria

Design criteria are the same as given in the mechanical discussion for the frequency reference oscillator.

Parametric Data

The voltage regulator shares a common cold plate with the frequency reference oscillator and current protection circuit. Weights and volumes of the voltage regulator portion of the package are given in Table 45. Weight and volume are independent of variations in input frequency.

Cooling requirements for the common cold plate are determined by the requirement to maintain a cold plate temperature of 150°C in the voltage regulator portion. Figure 66 shows variation of coolant inlet temperature with flow rate for the two megawatt design. Curves of weight and volume as a function of system output power are not shown because a relatively small variation occurs in these parameters.

TABLE 45
VOLTAGE REGULATOR
WEIGHTS AND VOLUMES

Voltage (volts)	20	20	20	20	100	100	100	100	300 & 600	300 & 600	300 & 600	300 & 600
Power (megawatts)	0.5	1.0	2.0	5.0	0.5	1.0	2.0	5.0	0.5	1.0	2.0	5.0
Weights (lbs)												
50 cps	19.92	19.92	23.40	21.90	20.30	20.30	23.35	21.90	20.20	20.20	23.10	21.90
5000 cps	20.42	20.42	23.50	21.90	20.58	20.58	23.50	21.90	20.42	20.42	23.50	21.90
Volume (cu.ft.)												
50 & 5000 cps	0.479	0.479	0.616	0.567	0.479	0.479	0.616	0.567	0.479	0.479	0.616	0.567

Problem Areas

Problem areas are the same as discussed in Part H for the frequency reference oscillators.

Analysis and Recommendations

As noted in Table 45, voltage regulator size and weight are a relatively small portion of those for a complete power system and are nearly constant at all voltages, frequencies, and power levels considered. Thus, the voltage regulator mechanical design has little affect on the choice of a design point, which must depend on consideration of all the electrical and mechanical parameters of a complete power system.

Weight of electrical parts is independent of frequency; however, the weight variation shown in Table 45 represents a slight variation with total package weight of the percentage of package weight required for the structure.

Figure 66 shows variation of coolant inlet temperature with flow rate for the two-megawatt design. A coolant flow rate of two pounds per minute is recommended.

K. CURRENT PROTECTION CIRCUIT

The function of the current protection circuit is to shut down the power converter if the load current exceeds 1.25 per unit. Shutdown is necessary to protect the inverter switching elements and rectifier diodes from the high internal temperatures generated by prolonged overload currents.

As explained previously, any increase in current capacity beyond one per unit results in significantly increased weight in the power inverter commutating components. The figure of 1.25 per unit was chosen to be a reasonable compromise between light weight and reliable operation. It is difficult to reliably sense currents less than 1.25 per unit, and the current protection circuit would be likely to cause false shutdown.

Electrical Design

Description

The current-protection circuit consists of one or more current transformers with associated rectifiers, a bistable Schmitt trigger, and an amplifier. One current transformer is used in conjunction with each power rectifier at the a-c input to the rectifier. Hence, the 5-megawatt power converters require eight current transformers while the lower power systems need only one.

The current transformers provide the inputs to the protection circuit; the outputs go to the frequency reference oscillator and the input circuit breaker. The current-protection circuit receives power from a 28-volt d-c control bus.

Operation

The operation of the current protection circuit is explained with the aid of Figure 72. Note that only two current transformers are shown in the diagram, whereas either one or eight is actually used. This was done to simplify the drawing while showing the means of using more than one current transformer.

The circuit functions as follows: During normal operation the a-c current flowing through the primary winding of each current transformer causes a proportional current flow through the secondary, which results in an a-c voltage across the burden resistor. The primary is formed by passing the power bus once through the core window of the current transformer. The secondary voltage, proportional to primary current, is rectified and applied to point A in the circuit.

The circuit parameters are chosen such that normal operation does not cause breakdown of Zener diode CRL. Thus, transistor

Q1 in the Schmitt trigger does not conduct, and the circuit remains in its normal state with Q2 conducting.

When an overload causes higher than normal current in one of the a-c power buses, the secondary voltage of the associated current transformer rises. When the voltage becomes high enough, corresponding to 1.25 per unit load current, CR1 breaks down, causing Q1 to conduct. This turns off Q2, causing Q3 and Q4 to turn on. The Schmitt trigger "latches" itself in this new condition with Q1 conducting.

The conduction of transistor Q3 provides a "stop" signal to the frequency reference oscillator, causing it to cease operating immediately. At the same time Q4 energizes the trip coil of the input power circuit breaker, causing the breaker to open after a few milliseconds time delay. The system is effectively shut down before the breaker opens because of the loss of the frequency-reference signal.

However, in the case of the systems using SCR inverters, the SCR's that were conducting at the time of the fault continue to conduct, and the breaker is required to interrupt the resulting current.

After the cause of overload is removed the power converter may be restricted by applying a momentary positive voltage to terminal GCl, causing the Schmitt trigger to revert to its normal state.

Design Criteria

The principal design criteria for the current protection circuit are that it be fast acting and accurate, since the power inverters are not designed to withstand prolonged overloads of more than 1.25 per unit current. The circuit chosen is capable of acting within a time period of a few milliseconds; accuracy is maintained by using a Zener-diode reference element and by maintaining control-bus voltage at a constant value.

Parametric Data

The electrical parametric data for the current-protection circuit is shown in Table 46. It is noted that the current-protection circuit makes up a very small portion of the total weight and losses of the power-conversion system.

One size of current transformer is used for all designs. The different current levels and frequencies are accommodated by changing the burden on the transformer.

Problem Areas

Because the current protection circuit has very fast response it is difficult to start the power converter under load. The

TABLE 46
CURRENT PROTECTION CIRCUIT
ELECTRICAL PARAMETRIC DATA

Output Voltage (kilovolts)	5, 5, 20	0.6 or 5
System Rated Power (megawatts)	0.5, 1, 2	5
Number of C.T.'s	1	8
Heat Loss per C.T. Including Burden	20 watt	20 watt
Weight per C.T.	1.2 pound	1.2 pound
Number of Rectifiers	1	8
Heat Loss Per Rectifier	1 watt	1 watt
Number of Schmitt Triggers	1	1
Heat Loss per Trigger	8 watt	8 watt
Number of Amplifiers	1	1
Heat Loss per Amplifier	14 watt	14 watt
Total Weight of Electrical Parts	2.3 pounds	10.7 pounds
Total Heat Loss	43 watt	190 watt

inrush current may trip the current protection circuit. Setting the current protection circuit at a higher trip point is not the solution because some of the power inverters may fail to commute at more than 1.25 per unit load current. If enough inverters fail to commute, the power converter will not start, and some of the inverter switching elements may be destroyed. Hence, the only safe way to start the power converter is under the condition of no load.

Analysis and Recommendations

The current protection circuit protects the power conversion equipment but not the ion engine loads. It is very likely that a faulted engine could draw enough current to destroy itself without ever causing converter load to exceed 1.25 per unit limit. This is a result of the large number of ion engines connected in parallel to the single power converter. Therefore, auxiliary protection means are required for the engines.

Furthermore, effective protection of the power conversion equipment requires an input circuit breaker capable of interrupting, in the 5-megawatt, 300-volt system, more than 16,000 amperes d-c. Developing such a breaker to work in a vacuum will be a formidable task.

Both of these problems can be alleviated by changing the power converter to a multi-channel system with the ideal situation being one channel for each engine.

Therefore, it is recommended that a study be made to determine the form and parameters of a multi-channel power conversion system. Another benefit to be derived from this design philosophy is greater system reliability.

Mechanical Design

The frequency reference oscillator, voltage regulator, and current-protection circuit are combined in a single package. The portion of the total package weight and volume that is attributed to the current protection circuit is presented here.

Description

The construction is described previously in the mechanical discussion for the frequency reference oscillators.

Design Criteria

Design criteria are the same as given in the mechanical discussion for the frequency reference oscillator.

SECTION IV
RELIABILITY

Parametric Data

The current protection unit shares a common cold plate with the frequency reference oscillator and voltage regulator. Weights and volumes of the current protection circuit portion of the package are given in Table 47. Weight and volume are independent of input frequency.

Cooling requirements for the common cold plate are determined by the requirement to maintain a cold-plate temperature of 105°C in the voltage regulator portion. Figure 66 shows variation of coolant inlet temperature with flow rate for the two-megawatt design.

Problem Areas

Problem areas are the same as discussed in Section 8 concerning frequency-reference oscillators.

Analysis and Recommendations

As noted in Table 45, size and weight of the current-protection circuit are small compared to a complete power system, and are virtually constant for all designs except the five-megawatt systems. Thus, the choice of a design point, based on consideration for all the parameters of a complete power system, should not be affected by mechanical characteristics of this portion.

Weights in Table 45 are seen to vary slightly at different frequencies, voltages, and power levels, although the weight of electrical parts is constant for all but the five-megawatt designs. This apparent inconsistency reflects the fact that the percentage of structural weight required for a given package increases as the total package weight decreases. Thus, the structural weight required for the current-protection circuit is dependent on the total weight of the package of which it is a part, including the frequency-reference oscillator and voltage regulator.

Coolant requirements are dictated by the voltage regulator, for which the variation of coolant inlet temperature with flow rate is given in Figure 66. From this figure, a flow rate of two pounds per minute is recommended.

TABLE 47

CURRENT PROTECTION CIRCUIT

WEIGHTS AND VOLUMES

Voltage (volts)	20	20	20	20	100	100	100	100	300 & 600	300 & 600	300 & 600
	0.5	1.0	2.0	5.0	0.5	1.0	2.0	5.0	0.5	1.0	2.0
Power (megawatts)	0.5	1.0	2.0	5.0	0.5	1.0	2.0	5.0	0.5	1.0	2.0
Weights (lbs)	4.38	4.38	4.43	25.4	4.46	4.46	4.43	25.4	4.43	4.43	4.38
	4.49	4.49	4.46	25.4	4.51	4.51	4.46	25.4	4.49	4.49	4.46
Volume (cu.ft.)	0.036	0.036	0.036	0.076	0.036	0.036	0.036	0.076	0.036	0.036	0.036
50 & 5000 cps	0.036	0.036	0.036	0.076	0.036	0.036	0.036	0.076	0.036	0.036	0.076

RELIABILITY

Reliability is defined as the probability that a device will perform its intended function for a specified period of time. Thus, a true measure of reliability can only be a quantitative one. The reliability of an electric system depends upon the reliability of its individual components and upon the circuits in which they are used.

One way to increase the reliability of the individual components is to reduce the stresses (voltage, current, temperature) to which they are subjected. This factor has been taken into account in this study. The ratings of the components are not exceeded under any anticipated conditions of operation, and the components will normally operate far below their maximum ratings.

Another way to increase reliability is by careful screening and pre-testing of components to uncover potential failures. This process has been successfully applied in the Minuteman missile program, and it is presumed that a similar program would be required for the power conditioning equipment presently being studied.

Two effective ways of improving system reliability are to minimize the number of components used, and to incorporate redundancy in the electric circuits. Redundancy, as such, has not been incorporated since it would violate the criterion of minimum weight. However, a certain amount of redundancy is inherent in the circuits used. In particular, the failure of any one component, such as a controlled rectifier, does not cause a catastrophic failure of the inverter. The only effect would be a reduction in the power output. Similarly, the loss of a power diode in the rectifier assembly or the loss of a shunt resistor-capacitor will not affect the output power, and system integrity will be maintained. The rectifier assembly peak-inverse-voltage rating is at least 2.5 times the peak-inverse voltage seen under normal system operation. Since the diodes normally fail shorted, the remaining diodes of the assembly are capable of withstanding the increased voltage stress. Thus, the system reliability is enhanced by the particular circuits chosen.

As stated in the inverter circuit write-up, the design having the least number of parts is likely to have the best reliability. Therefore, the inverters having 24 modules are preferred over those that require more.

The power-conversion-equipment reliability could be enhanced by incorporating redundancy in the drive amplifier. For example, two complete drive amplifiers could be included in a system, with automatic changeover in case of a failure. This would probably be desirable in an actual system because a failure in the drive amplifier would result in at least a partial power failure of the system.

High reliability of the input filter is assured by using a large number of parallel capacitors, each with its own fuse. By including a few more than the minimum necessary number of units, the failure of several units can be tolerated without degrading the performance of the power conversion system. This simple form of redundancy has proven very effective in previous applications. Note, however, that the parametric data for weight, losses, etc., do not include any redundant elements.

Reliability of the voltage regulator has been enhanced by using circuits that are capable of functioning properly even with severe degradation of components. However, the reliability of the regulator is limited by the fact that it contains a counter which operates in a serial fashion. In common with all counters, the failure of the single stage causes a degradation in performance. The counter will not count beyond the failed stage. Failure of a single stage will reduce the range of voltage regulation which may or may not cause critical system degradation, depending on what is subsequently required of the regulator.

SECTION V

SUMMARY

SUMMARY

The weight, volume and efficiency of the d-c to d-c converters studied is summarized in this section. The summary is presented in Tables 48, 49 and 50. The tabulated data in these tables are based on an inverter switching frequency of 1000 cycles per second. This switching frequency is a reasonable basis for this summary but does not necessarily result in the optimum converter system.

The weight, volume and efficiency of each functional block are listed for each system studied. The total weight, volume and efficiency of each system is a result of summing the data for each functional block. The weight, volume and efficiency of the one megawatt, 50 volt input, high temperature tube system is based on the input filter, inverter and power rectifier sections only. The determination of parametric data for the remaining functional blocks for the high temperature system was not within the scope of this study program. However, a reasonable estimate of the data for the power transformer, output filter, drive amplifier and control circuits can be made by using the data for the one megawatt, 20-volt and 100-volt input systems. Using these figures the high-temperature tube system parameters would lie in the following ranges:

	Min.	Max.
Weight (lbs)	10,708.1	11,647.7
Volume (cu. ft.)	162.5	172.9
Total Losses (kw)	279.0	316.9
Efficiency	76.0%	78.1%

The data found on Tables 48, 49 and 50 do not include the effects that radiation shielding, interconnecting conductors and radiators have on d-c to d-c converter systems. When these items are considered in the final overall system evaluation, the high temperature tube systems may become more attractive.

The data for the frequency reference oscillator, voltage regulator and the current protection circuit have been combined and presented under the heading "control circuits" in the summary tables. This was done since none of the control functional blocks contribute appreciably to the system weight, volume or losses.

The weight, volume and efficiency of the input filter for the 20- and 100-volt input systems are not shown since these systems use transistor inverters that require no input filter. (See Page 22.)

TABLE 48

WEIGHT SUMMARY

P _{out} & V _{out}	V _{in}	FUNCTIONAL BLOCK WEIGHT - (LBS)							Total Weight	Specific Weight (lbs/kw)
		Input Filter	Inverter	Pwr. Xfmr.	Pwr. Rect.	Output Filter	Drive Amp	Cont. Ckts.		
500 kw	20	-	2110	1570	37.6	200	195.2	31.4	4,144.2	8.26
	100	-	391	1215	37.6	200	48.0	28.6	1,920.2	3.84
	300	665	425	1095	37.6	254	45.6	30.8	2,553.0	5.1
	600	615	361	1095	37.6	254	45.6	30.8	2,439.0	4.87
1 mw	20	-	4220	3130	58.3	354	294	32.7	8,089	8.09
	50	1940	5770	-	166.4	-	-	-	*7,832.0	*7.83
	100	-	782	2430	58.3	354	63.5	28.6	3,716.4	3.71
	300	1278	610	2090	58.3	443	45.6	30.8	4,555.7	4.55
5 kv	600	1206	483	2090	58.3	443	45.6	30.8	4,356.7	4.35
2 mw	20	-	8450	6820	143.5	844	588	31.15	16,876.7	8.44
	100	-	1564	5230	143.5	844	116.8	31.0	7,929.3	3.96
	300	2550	1220	4620	143.5	1098	93.3	33.2	9,758	4.89
	600	2410	983	4620	143.5	1098	93.3	33.2	9,381	4.68
5 mw	20	-	21,250	15,900	281	2539	1469	51.7	41,490.0	8.29
	100	-	3920	12,300	281	2539	360	51.9	19,451.0	3.89
	300	6470	3770	10,300	281	3490	367	61.7	24,739.0	4.94
	600	6200	3124	10,300	281	3490	367	61.7	23,823.0	4.77

Inverter Switching Frequency = 1000 cps

*These numbers are based on the three functional blocks indicated. (See page 196.)

TABLE 49

VOLUME SUMMARY

P _{out} & V _{out}	V _{in}	FUNCTIONAL BLOCK VOLUME -CU. FT.							Total Volume
		Input Filter	Inverter	Pwr. Xfmr.	Pwr. Rect.	Output Filter	Drive Amplifier	Cont. Ckts.	
500 kw	20	-	92.7	7.28	1.07	1.29	3.0	0.67	115.01
	100	-	15.7	4.55	1.07	1.29	0.88	0.63	25.12
	300	11.03	11.2	3.70	1.07	1.56	0.16	0.67	29.39
	600	11.03	9.7	3.70	1.07	1.56	0.16	0.67	27.89
1 mw	20	-	185.2	14.6	1.93	2.2	4.62	0.67	209.22
	50	23.0	123.	-	4.9	-	-	-	*150.9
	100	-	31.4	7.36	1.93	2.2	1.40	0.63	44.9
	300	18.8	17.5	2.61	1.93	2.92	0.16	0.67	44.59
2 mw	20	-	12.3	2.61	1.93	2.92	0.16	0.67	38.29
	100	-	371	38.1	3.61	6.25	9.26	0.76	428.9
	300	37.6	62.8	21.4	3.61	6.25	2.65	0.76	97.47
	600	35.4	35.0	15.8	3.61	8.45	0.16	0.81	101.43
5 mw	20	-	24.6	15.8	3.61	8.45	0.16	0.81	88.83
	100	-	931	74.1	6.0	27.2	23.1	0.72	1062.1
	300	101.5	157.6	50.3	6.0	27.2	7.43	0.76	249.2
	600	97.1	97.5	37.3	6.0	36.8	1.34	0.87	281.3
5000 v	600	97.1	86.6	37.3	6.0	36.8	1.34	0.87	278.07

Inverter Switching Frequency = 1000 cps

*This number is based on the three functional blocks indicated. (See page 196.)

TABLE 50

EFFICIENCY SUMMARY

P _{out} & V _{out}	V _{in}	FUNCTIONAL BLOCK LOSSES - KW								Total Efficiency
		Input Filter	Inverter	Pwr. Xfmr.	Pwr. Rect.	Output Filter	Drive Amp	Cont. Ckts.	Total Losses	
500 kw	20	-	36.6	38.4	1.431	1.140	1.65	0.546	79.76	86.5
	100	-	10.6	21.2	1.431	1.140	0.372	0.510	25.25	93.1
	300	1.192	8.5	11.5	1.431	1.341	0.072	0.517	23.55	95.6
	600	0.080	6.5	11.5	1.431	1.341	0.072	0.517	21.4	96.0
1 mw	20	-	73.2	78.0	2.813	1.552	3.3	0.577	159.4	86.5
	50	0.548	190.0	-	43.00	-	-	-	233.5	** 81.0
	100	-	21.2	42.7	2.813	1.552	0.744	0.510	69.5	93.6
	300	0.380	15.5	18.2	2.813	1.756	0.072	0.517	39.23	96.4
	600	0.148	12.0	18.2	2.813	1.756	0.072	0.517	35.5	96.7
2 mw	20	-	146.4	160.0	5.590	2.175	6.75	1.26	322.17	86.1
	100	-	42.4	91.2	5.590	2.175	1.488	1.26	144.11	93.4
	300	0.760	31.0	36.7	5.590	2.535	0.120	1.26	77.9	96.5
	600	0.298	24.0	36.7	5.590	2.535	0.120	1.26	70.4	96.6
5 mw	20	-	366	380.0	20.26	9.66	16.9	0.367*	793.7	86.5
	100	-	106	217.0	20.26	9.66	3.76	0.365*	357.0	93.1
	300	1.880	81.4	99.0	20.26	12.24	0.608	0.407*	215.7	95.8
	600	0.730	66.1	99.0	20.26	12.24	0.608	0.407*	199.3	96.2

Inverter Switching Frequency = 1000 cps

*Output Voltage = 600 v

**This number is based on the three functional blocks indicated. (See page 196.)

SECTION VI
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

This report presents the parametric data of several d-c to d-c converter systems. Analyses and recommendations have been made for each functional block in the preceding section. Conclusions and recommendations concerning the d-c to d-c converter systems in general are discussed in this section.

A. Conclusions

1. The results of the study show that converter systems become more attractive at the higher input voltages. Converter systems with relatively high input voltages tend to be more efficient, less complex, and lighter than systems with lower input voltages. The upper voltage limit is determined by the voltage rating of the individual circuit components and the source.
2. The weight, efficiency, and volume of the converter system are dependent on the inverter switching frequency. It is not obvious how the system parameters vary because the parameters of each functional block do not change in the same direction or magnitude with a change in switching frequency. The switching frequency that results in an optimum converter system can be determined by investigating a system at a fixed power level with specified load requirements.
3. The functional blocks using high temperature tubes as switching devices and rectifiers are heavier, larger, and less efficient than their semiconductor counter-parts. The higher operating temperatures of the tube devices tend to permit a lighter and smaller cooling system. However, the greater heat losses in the tubes offset this advantage. It appears that the prime advantage of the tubes is their resistance to nuclear radiation.
4. The single-channel configuration studied presents major problems in areas of circuit breakers and reliability. The main circuit breaker in the single-channel system must interrupt extremely large direct currents, which necessitates circuit breaker development. Additional effort is needed to overcome this problem and to improve the reliability deficiencies inherent with any single-channel configuration.

B. Recommendations

The work done during this study investigates the basic building blocks of a converter system. It is recommended that future efforts be directed toward expanding this investigation to give an improved picture of how the converter parameters are affected when functional blocks are combined to

form complete systems. A multichannel configuration would help to improve reliability and would circumvent the main circuit breaker problem.

It is recommended that a parametric study be based on a system with a fixed output voltage and power level that conforms to the requirements of future space propulsion systems. The prime objectives of this study should be: (1) develop conceptual designs that permit a comparison of single channel versus multichannel configurations, and (2) develop conceptual designs to show what effect the input voltage and the type switching device has on total system weight and efficiency. The recommended study would investigate a single-channel and a multichannel configuration. Semiconductor switching and rectifier devices would be compared to high-temperature tube switching devices and rectifiers in each configuration. The results of the parametric study would show the most desirable input voltage, converter configuration, and switching device for the output voltage and power level considered. The parametric study will also show the weight and efficiency penalties involved in deviating from the optimum condition.

SECTION VII
BIBLIOGRAPHY

BIBLIOGRAPHY

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SECTION VIII

APPENDIX

APPENDIX

Electric Engine Arc Suppression

Voltage breakdown and arcing between the high-voltage accelerating electrodes of ion thrusters present a major problem to the development of d-c to d-c converters for these thrusters. The short circuit conditions caused by this arcing phenomena adversely affects the weight, volume, and reliability of the d-c to d-c converter. Analysis and recommendations for the arcing problem is presented below.

A description of the breakdown and arcing phenomena is presented in AIAA Paper No. 63057.¹ The following conclusions are based on the information in this paper.

1. The initial breakdown between screen and anode is probably caused by a speck of contaminant on one of the electrodes. The contaminant may be condensed mercury fuel, vacuum pump oil, or a film of material deposited on the plates during manufacture.
2. Once the arc begins, it is sustained by the vaporization of the electrodes due to the heat generated by the arc.
3. When the arc current is sufficiently reduced, less vapor is formed and the arc is extinguished very suddenly.

It is stated in the paper that the power supplies utilized LC filters at their outputs. The effect of the arc on this type of supply is as follows.

Initially, the capacitor is charged to a voltage of several thousand volts, and load current is flowing in the inductor. When a breakdown occurs, the capacitor discharges into the arc, delivering a high current for a short time, sufficient to sustain the arc through the vaporization process.

Soon the capacitor becomes discharged, the arc current is reduced and the arc extinguishes itself. However, this leaves the power supply with a discharged capacitor. So the capacitor begins to charge up again, through the choke, in the manner of a tuned circuit. Elementary circuit theory shows that in a tuned circuit of this kind the capacitor voltage will overshoot, and may reach twice its steady state value. That the overshoot does in fact occur is shown in Figure 6 of the referenced paper.

¹ Elastic Breakdown and Arcing in Experimental Ion Thruster Systems, by John B. Stover, Lewis Research Center, NASA, Cleveland, Ohio, presented at Electric Propulsion Conference, March-1963.

Apparently, the high voltage stress caused by the overshoot initiates another breakdown, resulting in another arc. This process may repeat several times before a sustained arc is developed. There are also cases wherein a sustained arc does not develop, even after several breakdowns have occurred.

The reason that sustained arcs occur at times is not at all clear, but it may be due to repeated localized heating of the electrodes, with insufficient cooling time between arcs, so that a hot spot is produced that is capable of sustaining an arc.

This condition may be aggravated by the presence of mercury ions in the gap, in higher than normal concentration because thruster operation has been disrupted.

There is another possible aggravating condition. If the timing of the first arc is just right with respect to the phase of the a-c power line, the capacitor-inductor circuit will receive an additional "kick" of voltage due to the peak of the a-c waveform, resulting in higher overshoot and more energy dissipated in the next arc. This will cause greater localized heating and increase the chances of the arc striking the same spot again and again, until a sustained arc develops. This conjecture is supported by an examination of Figure 6 of the referenced paper. It will be noted that arcs occurred at approximately 8 millisecond intervals, corresponding to the period of a full wave rectified, 60 cycle waveform.

Based on the above analysis, the following recommendations are made:

1. Reduce the value of capacitance in the power supply filter. This would reduce the energy available to be dissipated in the arc and would reduce local heating of the electrodes. Hence, the probability of a second arc in the same spot would be reduced.
2. Where a-c input power is available, use power supplies having multiphase transformers and rectifiers. This would have two advantages. First, the difference between the steady-state d-c and the peak a-c would be reduced, resulting in less "kick" available for aggravating overshoot. Second, the ripple is less, allowing use of smaller output filter elements with less energy storage capacity.
3. Use voltage suppressors across the thruster and/or power supply terminals. These would have the dual benefits of eliminating overshoot, and protecting the power supply from damage caused by excessive transient voltages. The voltage suppressors could take the form of avalanche diodes, which have a characteristic similar to Zener diodes, except at higher voltages.

4. Use square-wave a-c power to the transformer-rectifier units. This would require the least filtering of all, and there would be no peak voltage to aggravate overshoot.
5. Use power supplies having the minimum power capacity actually needed. This will reduce the arc energy and the resulting heating. Running several thrusters from one big supply should be avoided if possible, because it may be possible to destroy a thruster by excessive arc current.

Based on the recommendations presented, it is suggested that further investigations be made to provide the necessary voltage protection for the d-c to d-c converter systems considered in this study and for the reduction of engine faults. These recommendations could also be evaluated experimentally in conjunction with NASA's continuing development of ion thrusters.